Section 2
Standard Methods For Identifying
Bankfull Channel Features and Channel Migration Zones

PART 1. BANKFULL CHANNEL FEATURES

No change to this section, see existing Board Manual

PART 2. CHANNEL MIGRATION ZONES

PART 2. CHANNEL MIGRATION ZONES

2.1 Introduction

This manual is a technical supplement to the forest practices rules to assist landowners, foresters and others in determining whether a Channel Migration Zone (CMZ) is present in a proposed forest practice activity area and, if so, to assist in the delineation of the CMZ. The forest practices rules define a CMZ as *"the area where the active channel of a stream is prone to move and this results in a potential near-term loss of riparian function and associated habitat adjacent to the stream, except as modified by a permanent levee or dike. For this purpose, near-term means the time scale required to grow a mature forest (**WAC 222-16-010**)."*

This manual is organized to first help the user distinguish if the stream segment adjacent to a proposed forest practice activity is prone to migration (Section 2.2). Once it has been determined that channel migration has historically occurred or is occurring along the segment, Section 2.3 provides technical guidelines and likely scenarios for CMZ delineation. Section 2.4 provides possible CMZ review steps and a description of where and what type of additional analyses may be necessary. A glossary of technical terms used in this manual can be found in Section 2.6.

In delineating a CMZ, we attempt to anticipate the type and scale of large channel-changing events that may occur during a 25, 50, or 100-year flood event – the scale of events for which we have some predictive capability. Careful evaluation of field evidence will help the landowner determine the limit of channel migration over the near-term future. An understanding of general river processes may also be helpful to the landowner. To this end, a technical background section (Section 2.5) is included, and users of this manual are encouraged to become familiar with the concepts offered.

2.2 Determining if Channel Migration Is Present

Prior to delineating a Channel Migration Zone adjacent to any harvest unit, one first needs to determine if channel migration has historically occurred. Evidence that channel migration is occurring now or has occurred in the past (1900 to present) can be observed by viewing topographic maps and aerial photographs and by observing lines of evidence on field inspections. This section describes the two distinct steps to perform this determination: 1) an Office Review; and 2) a Field Evaluation.

Office Review to Determine Channel Migration

The purpose of the Office Review is to look for obvious indicators of past channel movement, to gather information about channel features, and to facilitate and complement the field evaluation. Use the CMZ Office Review Form in conjunction with historical and current aerial photography and topographic maps to do this review. The text following the form provides technical guidance for questions on the form.

CMZ Office Review Form

Collect appropriate tools, including USGS 7 ½' Quadrangle Topographic Maps, current and historic aerial photos (oldest and some years in between oldest and most recent is recommended). List the source, year, and scale of all historical information used (for example DNR aerial photography, 1995, 1:12000):

Examine upstream and downstream from the harvest unit boundaries as necessary to determine stream behavior. If the stream of interest is not mapped on the USGS Topographic Map, or if channel features are too small to be visible on the aerial photos, proceed to the Field Evaluation Form.

Question 1: Do you observe obvious channel movement between aerial photo years?

No. Go to Question 2.

Yes. Proceed directly to **<u>Section 2.3 – Delineating the Channel Migration Zone.</u>**

Question 2: Using Board Manual guidance, evaluate valley confinement from USGS Topographic Map or aerial photos.

_______ Valley floor is significantly wider than the channel. Channel migration may be occurring.

_______ Valley floor is very narrow, obviously less than twice as wide as the channel. If you can clearly see this circumstance on the aerial photographs, it is unlikely that channel migration is occurring.

In both cases, proceed to Question 3.

Question 3: On the aerial photos, do you observe:

Yes	No	
_____	_____	Secondary Channels
_____	_____	Multiple Channels (braiding or anabranching)
_____	_____	Large Gravel Bars
_____	_____	Young Disturbance Vegetation
_____	_____	Eroding Banks
_____	_____	High Sinuosity
_____	_____	Wood Jams

If "yes" to 1 or more channel features, channel migration is likely to be occurring. Proceed to Field Evaluation to Determine Channel Migration.

If none of these channel features are evident on the aerial photos, proceed to Field Evaluation to Determine Channel Migration to confirm that no channel migration has historically occurred.

Observations of Channel Migration from Photos and Maps

For larger rivers, active channel migration is often readily observed on a single air photo or by comparing air photos and maps. Where channel migration is apparent, proceed directly from the Office Review Form to **Section 2.3 – Delineating the Channel Migration Zone.**

A lack of channel movement visible on aerial photographs does not mean that channel migration has not occurred. In particular, photos may be of limited value in observing the movement of small streams. If channel migration is not observed in the aerial photographs and topographic maps, proceed to the **Field Evaluation to Determine Channel Migration** (in this section) for final determination.

Determining Valley Confinement from Photos and Maps

Valley width is the area within the comparatively flat valley bottom, measured from the edges of significant changes in topography (typically the base of hills or mountains). In migrating channels, the valleys must be wide enough to accommodate lateral movement of the stream. The Forests & Fish Report (WSDNR et al., 1999) identifies streams potentially associated with a channel migration zone as those that are moderately confined or unconfined.

Aerial photography may be useful to estimate valley confinement. However, aerial photos must be viewed in stereo, otherwise the features of interest may not be apparent. From the photos:

1. Identify valley walls where hillslopes or other, significant topographic controls begin. Measure the average valley width along the segment.
2. Identify the width of the active stream channel (this includes areas currently under water, adjacent unvegetated areas, and vegetated islands). Measure the average channel width along the segment.
3. Determine the ratio of average valley width to average channel width (i.e., approximately less than 2 or greater than 2).

Topographic maps can also be used to estimate valley confinement:

1. Measure the average valley width between the contour lines that define the valley walls. The contour lines of the valley bottom will be broadly spaced, and those of the adjacent hillslopes will be more closely spaced (see Figure 1).
2. Observe how sharply angled the contour lines surrounding the channel are. Valleys that are tightly confined will have closely spaced contour lines that form a narrow upstream-pointing V-shape (see the stream labeled "Creek" in Figure 1). Unconfined valleys will have more widely spaced contours that form an open V- or U-shape (see Figure 1).
3. Estimate the average channel width from aerial photos or field knowledge.
4. Determine the ratio of average valley width to average channel width (i.e., approximately less than 2 or greater than 2).

It can be difficult to measure channel confinement from standard 7.5- minute topographic quadrangle maps (1:24,000 scale), especially for small channels because the channel widths are difficult to discern. Wherever possible, stream channel confinement estimated from topographic maps should be confirmed with aerial photographs and field observations. Where available, high-resolution topography from photogrammetry, LiDAR (Light Distancing And Ranging), and land surveys can be extremely useful in identifying channel features.

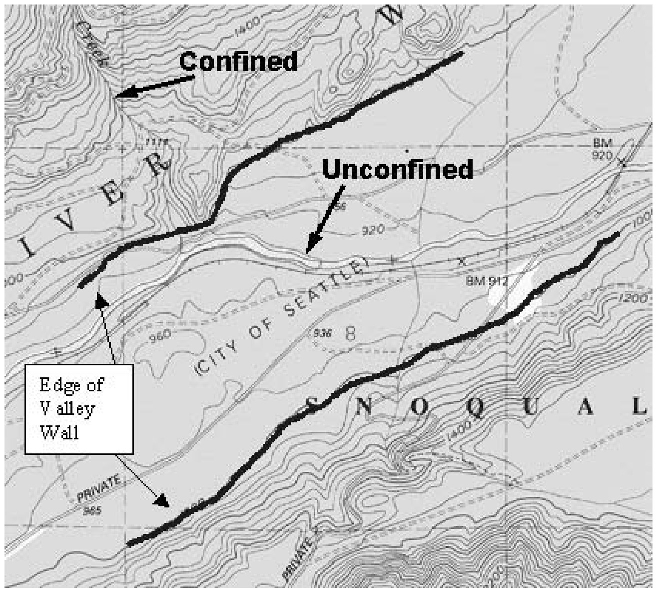


Figure 1. Examples of valley confinement using a topographic map.

Air Photo Observations of Channel and Floodplain Features

The following figures are examples of aerial photographs and a map that display one or more of the channel and floodplain features listed on the Office Review Form.

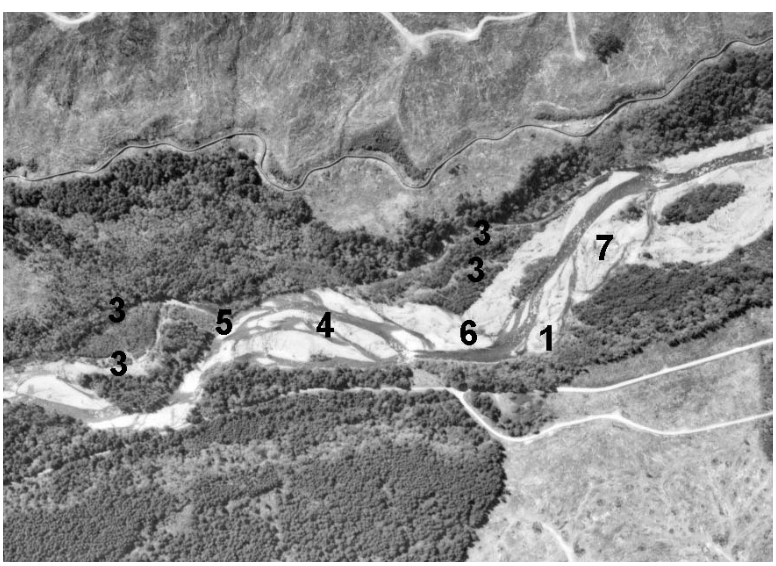


Figure 2. Examples of channel and floodplain features.

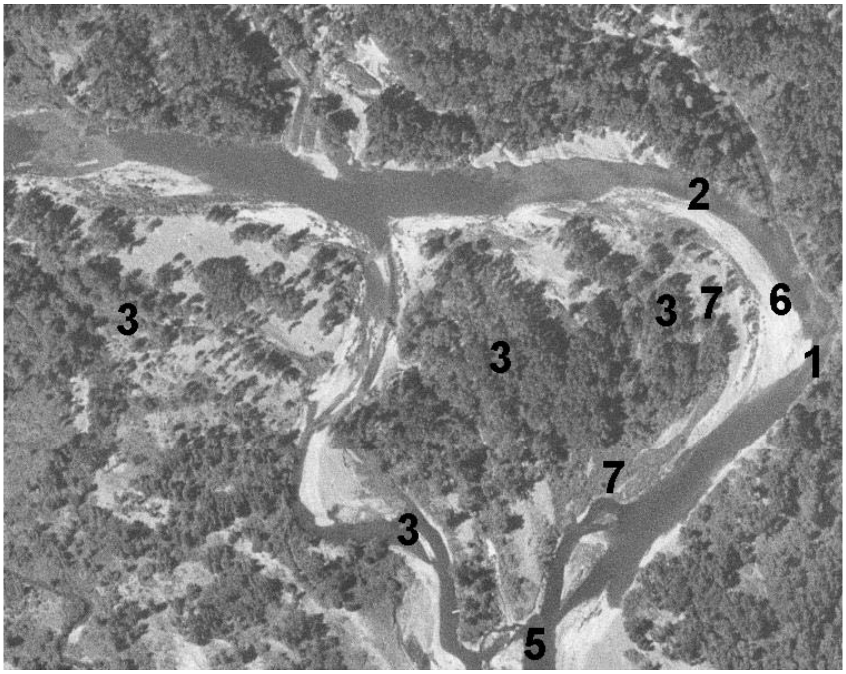
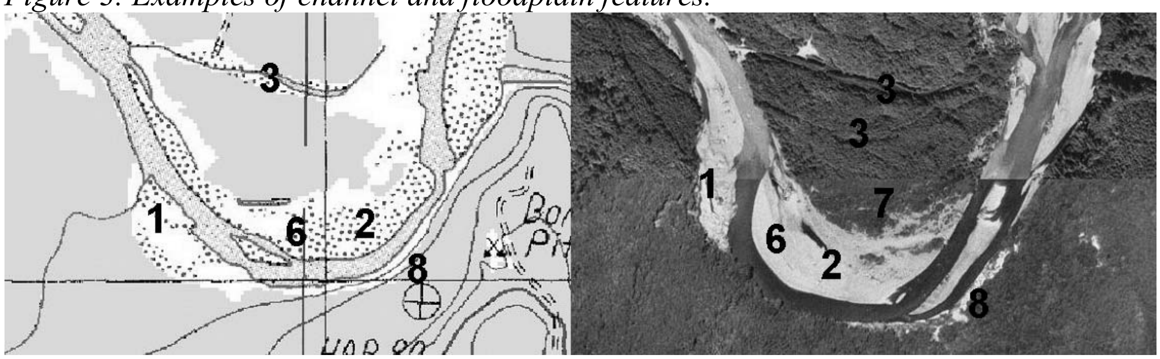


Figure 3. Examples of channel and floodplain features.

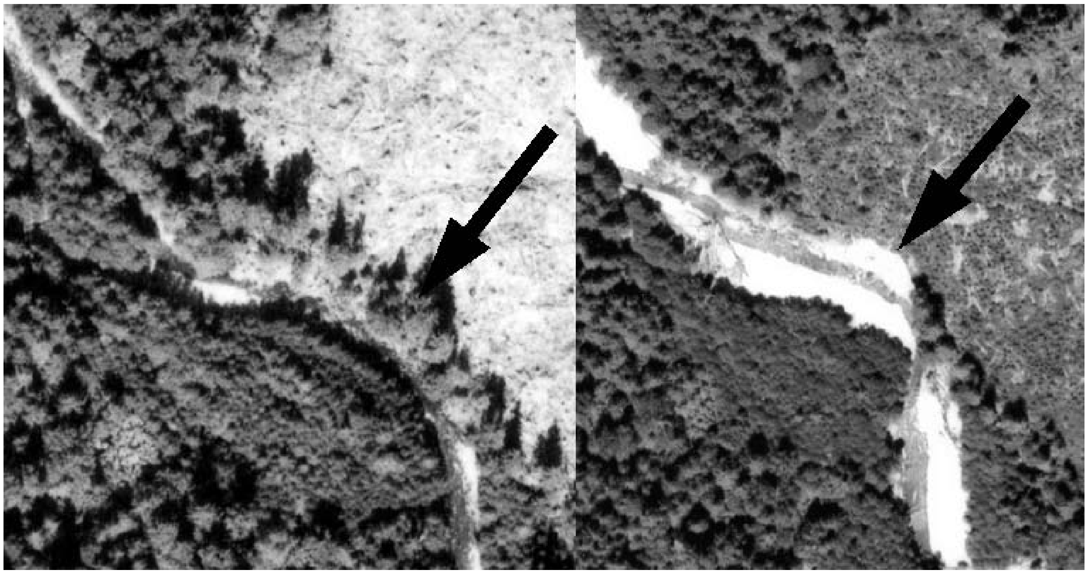


Figures 4a and 4b. Examples of channel and floodplain features.

Figures 2, 3, 4a, and 4b. Examples of channel and floodplain features: 1) obvious channel movement; 2) high sinuosity; 3) secondary channels; 4) braiding; 5) anabranching (multiple channels around vegetated islands); 6) large gravel bars; 7) young disturbance vegetation; 8) eroding bank; 9) log jams.

Air Photo Observations of Bank Erosion

Observable lateral movement of the channel may be due to avulsion or erosion processes. Avulsion is likely to involve floodplain surfaces, where erosion may involve higher floodplain and terrace edges. It may be possible to distinguish between these processes from examination of aerial photographs. An avulsion may isolate a portion of the floodplain between channels, whereas bank erosion will not. The exposed soils (scarp) of the eroding bank may also be observable in the photos. Bank erosion can be episodic and strongly correlated with flood frequency, so care must be taken to evaluate a sufficiently long period of time to determine if significant bank retreat is occurring within the segment. The office analysis time frame should include the entire length of the air photo record and/or cover at least two decades to account for impacts of larger events.



Figures 5a and 5b. Example of bank erosion between two sets of air photos.

Field Evaluation to Determine Channel Migration

The purpose of the field evaluation is to use field observations to determine if historical channel migration has occurred and, therefore, if a CMZ delineation is necessary. This is accomplished by working through observations of evidence in the Field Evaluation Table below. Evidence identified on the Field Evaluation Table is described in detail in the sections that follow the table.

When field evidence indicates channel migration to be occurring, proceed to **Section 2.3 – Delineating the Channel Migration Zone**. If no evidence of historical channel migration is found, then establish a riparian management zone from the bankfull edge of the stream (Board Manual Section 2, Part 1. Determining Bankfull Width). When experienced with the Field Evaluation Table, a field practitioner may find the **Flow Chart for Determining Channel Migration** found at the end of this section to be a useful field tool.

To conduct a field reconnaissance for evidence of channel movement, the entire floodplain within or adjacent to the project and, as necessary, some distance beyond the area of the forest practice should be walked to observe the character of the channel. Evidence of channel migration should be obtained from a homogenous channel segment. To establish a homogenous channel segment, follow the procedure in Section 2.3. Note: permission of adjacent landowners to access their property may be required.

Field Evaluation Form

Evidence Category		Observations	Next Step
Valley Confinement:	C1	The width of the valley floor is less than 2 times bankfull width of the channel.	No CMZ; delineate RMZ from bankfull edge.
	C2	The width of the valley floor is equal to or greater than 2 times the bankfull width of the channel.	CMZ may be present; continue to Lateral Activity category.
Lateral Activity:	L1	No lateral movement possible due to presence of bedrock bed and banks or other erosion-resistant material.	No CMZ; delineate RMZ from bankfull edge.
	L2	There is obvious lateral movement of the channel.	Proceed to delineating the CMZ.
	L3	Neither L1 nor L2 is true.	Continue to Vegetation category.
Vegetation:	V1	Along a representative channel, old growth conifer trees or stumps occur uninterrupted from higher terraces or valley walls down to both stream edges and there are no secondary channels.	No CMZ; delineate RMZ from bankfull edge.
	V2	There are age-progressive bands of trees or other linear vegetative features of channel migration on the floodplain.	The channel is migrating or has historically migrated; proceed to delineating the CMZ.
	V3	There is no vegetative evidence of channel migration (except, perhaps, interrupted old growth trees or stumps).	Continue to Secondary Channels category.
Secondary Channels:	S1	There are no secondary channels.	No CMZ; delineate RMZ from bankfull edge.
	S2	There are secondary channels on the floodplain and all bed elevations lie above the bankfull elevation of the main channel.	Historical channel migration may have occurred but was not identified by this evaluation. Proceed to the delineation of the historical migration zone (HMZ) in Section 2.3 for further evaluation.
	S3	There is at least one secondary channel on the floodplain with bed elevation at or below bankfull elevation.	The channel is migrating; proceed to delineating the CMZ.

Refer to Board Manual Section 2.2 for “Evidence Category” definitions.

Valley Confinement (C1-C2)

Measuring valley confinement is the first step in determining if CMZ delineation is necessary. Measuring valley confinement in the field is accomplished by measuring the width of the entire valley floor from hillslope to hillslope and comparing this value with the bankfull width of the stream. When characterizing the average bankfull width and average valley width for the channel segment, take enough measurements to provide an accurate representation of valley confinement. Where valley confinement is not obviously discernible, bankfull width and valley width should be measured and averaged from at least 10 evenly spaced cross-section transects along the channel segment.

If valley width is less than 2 times bankfull width, on average (C1), it is not necessary to delineate a CMZ. If valley width is approximately equal to or exceeds 2 times bankfull width, on average (C2), continue the evaluation.

Figures 6 and 7. Examples of a confined valley and an unconfined valley.

Before proceeding with the rest of the field evaluation, review the definitions of "terrace" and "floodplain" on the next page. These terms are defined to help with distinguishing between terraces and the floodplain surfaces where most of the field evidence for historical channel migration will be found.

Lateral Activity (L1-L3)

This category of field evidence is a screen for obvious indicators of lateral channel activity by identifying conditions where channel migration is unlikely and those where channel movement is apparent. Where neither condition described as L1 or L2 below are true or obvious, proceed with the evaluation (L3) and the vegetative indicators category below.

If the bed and banks of the stream are composed of bedrock or other erosion-resistant material, no lateral movement of the channel is possible (L1), and the RMZ will begin at the bankfull channel edge. Stream banks resistant to erosion are composed of materials such as hard rock or well-cemented alluvial deposits that can form stable vertical banks. These do not experience significant erosion (Figure 8). Cemented alluvial deposits often look similar to unconsolidated and erodible alluvial deposits, but display their resistance to erosion by showing resistance to removal of individual stones by hand and exhibit a non-retreating near-vertical bank (Figure 8). On these banks, tree roots are unlikely to be exposed but may "wrap" around the edge of the bank. Under-cutting of stream banks consisting of cohesive materials such as clay, or partially cemented or well-consolidated deposits may indicate relative stability or very slow erosion. Stream banks that are re-enforced with tree roots can be quite stable if the roots extend the full height of the bank and are not destabilized by undercutting from the stream channel (Figure 9). This occurs along relatively small channels and where bank materials have some natural erosion resistance (L3).

"*Terrace*," as defined here, is a former or relict floodplain no longer inundated by floodwater given the current climate. A non-floodable terrace surface is not considered to have the potential to be re-occupied by the river or stream under the current climate regime and natural wood loads; however, it could be susceptible to erosion by the stream. Some care must be taken when identifying surfaces as terraces because any land-use or management-induced loss of large woody debris may have resulted in the channel incising into its floodplain, temporarily stranding surfaces that are floodplain surfaces during times of natural wood loads.

Evidence of a terrace surface include, but are not limited to:

- No evidence of inundation by floodwaters -
    - No evidence of fine sediment deposition on the surface or embedded in tree bark or moss;
    - No flotsam hanging in the brush;
    - No stick or log jams on the surface; and
    - No evidence of flowing water on the surface, such as scour features, flattened grass or secondary channels formed by scour action of the modern river.
- There is soil development (presence of a deep A-Horizon or humus organic layer).
- There are noticeable differences in the geologic materials as compared with lower surfaces (e.g., glacial deposits versus Holocene alluvium).
- Vegetation on the surface is dominated by upland plant species, except where there are perched wetlands.
- The surface lies ABOVE the elevation of the 100-year flood inundation. Usually, this can be reasonably agreed to, taking into account evidence of incision and wood loss. It should be a rare situation where this elevation needs to be quantified.

"*Floodplain*," as defined here, is the area of the valley that can flood given the current climate and natural loads of LWD. The floodplain may contain surfaces at one or many elevations. The floodplain is the area to be evaluated for possible inclusion within the CMZ.

Evidence for a floodplain includes, but is not limited to:

- Flotsam hanging in the brush and log jams on top of the surface.
- Fine sediments are found in the tree moss and there may be abrasions of the lower tree trunks.
- Silt, sand or gravel are found immediately under the leaf layer.
- The alluvial materials consisting of silt, sand and gravel are uncompacted and unconsolidated.
- A wetter understory plant community with facultative wet and/or wetland obligate species is present. Disturbance species such as willow, cottonwood and alder are likely to be present in the overstory canopy.
- Evidence of flowing water, such as scour features, flattened grass or secondary channels formed by scour action of the modern river.
- The elevation of the surface lies near the elevation of the highest channel features (e.g., log jams and gravel bar surfaces).
- The surface lies WITHIN the elevation of the 100-year flood inundation. Usually, this can be reasonably agreed to, taking into account evidence of incision and wood loss. It should be a rare situation where this elevation needs to be quantified.

If some period of time has lapsed since a large flood event (e.g., greater than a 20+-year event), then evidence that relates directly to flooding of a surface may be muted.

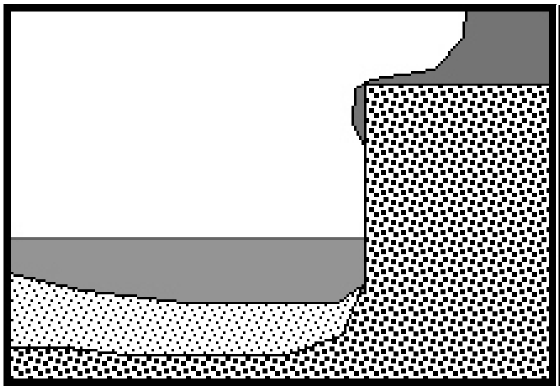


Figure 8. Illustration of erosion-resistant bank.

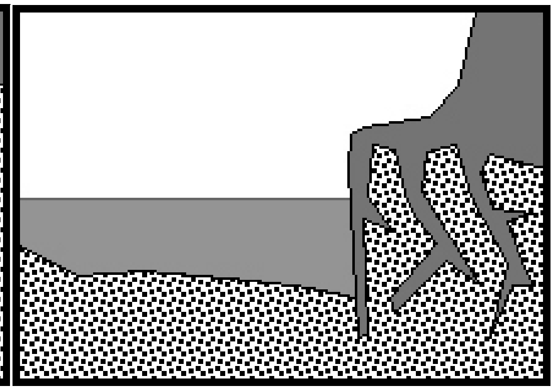


Figure 9. Illustration of root-stabilized bank.

Where it is obvious the channel is or has been moving laterally, proceed to delineating the CMZ (L2). Abandoned channels and extensive bank erosion are some obvious indicators. Stream banks susceptible to erosion are usually composed of the same size material currently being transported by the channel, as evidenced in the channel bed and bars. Eroding stream banks can be identified through the observation of frequent overhanging tree roots exposed in the bank above the stream channel, an indication that the bank has retreated a distance equal to the length of root exposure (Figure 10). The eroding bank is typically paired with a bar deposited on the opposite bank or downstream. Fan-like accumulations of the same material that the bank is composed of at the base of the slope can also indicate that the stream channel has eroded into the slope (Figure 11a). These accumulations are typically found in stream banks made of unconsolidated alluvium (sand, gravel, cobble), but can include more consolidated materials (clay, compacted or partially cemented silt or gravel) that accumulate in blocks at the toe (Figure 11b). A stream bank where the toes have been undercut can also indicate active bank erosion, particularly if bank failures are also observed along banks of similar material within the same stream channel segment (Figure 12). All these situations fall under L2. If it's unclear from field evidence that bank erosion indicates obvious lateral movement, continue with the evaluation from L3.

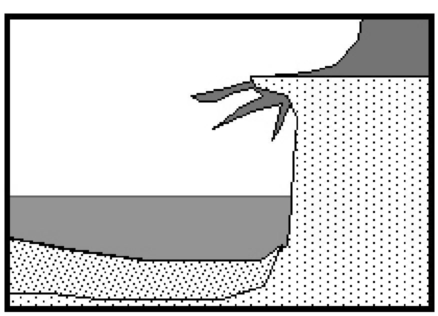


Figure 10. Illustration of root exposure as an indication of bank erosion.

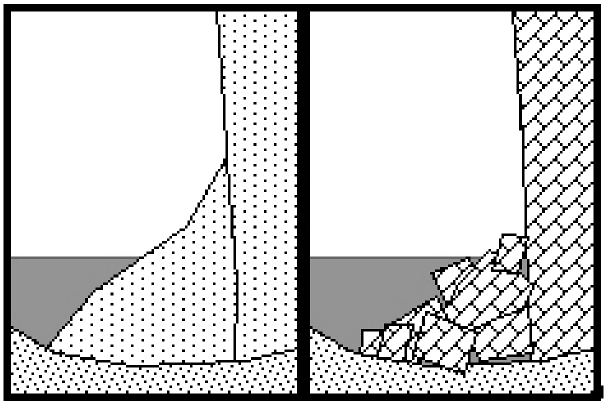


Figure 11a. *Figure 11b.*
Illustrations of accumulation of eroded material (Fig. 11a) and blocks of material (Fig. 11b) at base of bank.

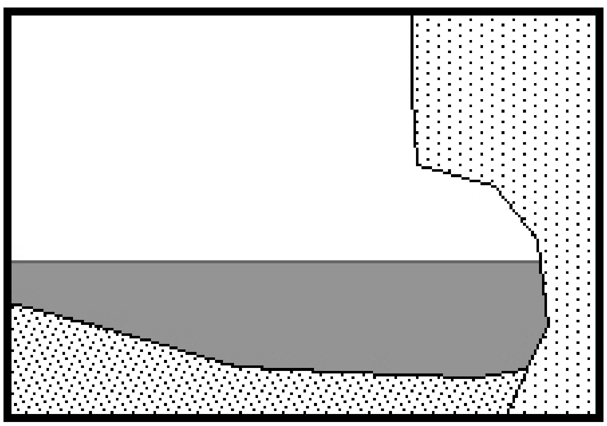


Figure 12. Illustration of an undercut stream bank.

Vegetative Indicators of Channel Migration (V1-V3)

Existing vegetation and historic vegetative features that are still present can provide significant indications of channel history within a given stream reach. Vegetation age is a reflection of the length of time that has passed since disturbance. Vegetation type or plant community can also reflect the type or severity of disturbance that has occurred. When used in conjunction with other channel indicators, vegetation patterns can greatly assist in the identification and delineation of channel migration zones, but are never sufficient evidence alone (i.e., the presence of old trees or stumps is not sufficient evidence to exclude an area from a CMZ).

Much of the land subject to Forest Practices regulation has been logged at least once. Often old-growth stumps and sometimes trees remain, bearing evidence of pre-settlement stand conditions. Old growth Douglas-fir and Western red cedar stumps are especially persistent within the forested environment. Surfaces that are covered with old-growth trees or stumps have not been disturbed by river influences within the time period reflecting the age of the trees or stumps. In general, stream-adjacent surfaces populated with persistent old-growth trees or stumps from valley wall to bankfull edge, uninterrupted by secondary channels, are considered to be upland terraces or stable floodplain. These surfaces are typically outside the influence of channel migration (V1) if they are not subject to channel migration through erosion or avulsion processes (L2). Where surfaces with old growth trees or stumps contain linear channel features without stumps or trees of the same age, proceed with the evaluation (V3) if there are no other vegetative indicators as described below (V2).

Patterns of vegetation can indicate areas disturbed by past channel activities (V2). Vegetation types often show up in linear patterns on a stream-adjacent surface. Age-progressive bands of vegetation along a stream reach can indicate meander migration that occurs as an active channel moves laterally away from a stream bank over time (Figures 3 and 4). Tree species such as alder can colonize natural linear features such as secondary channels or other deposition/disturbance edges on the floodplain. Caution must be used in this interpretation however, as vegetative bands can also represent non-stream influences such as orphaned road grades, skid trails, or gravel extraction sites.

A stream-adjacent wetland plant community such as red alder with a sedge understory may denote a low floodplain surface subject to frequent inundation (V2). A red alder/sword fern plant community indicates a drier site such as a re-colonized gravel bar, debris fan, or even an upland terrace. Surfaces with this vegetation can still flood, and their presence is inconclusive. Stream bank or terrace edges that have had sufficient time post-disturbance to develop a stable angle of repose are typically covered with timber and/or understory vegetation (V3). Non-bedrock channel features that are devoid of vegetation have been subjected to recent or recurrent scour/deposition (V2). If it's unclear from field evidence that vegetation patterns indicate channel migration, assume there is no vegetative evidence of channel migration and continue with the evaluation from V3.

Secondary Channels (S1-S3)

Floodplain river systems often have multiple types of interacting *channels*, which aid in floodplain building processes and the conveyance of water longitudinally and laterally. *Secondary channels* carry water (intermittently or perennially in time; continuously or interrupted in space) away from, away from and back into, or along the main channel. *Anabranch* channels are the most common form of secondary channel, which are a diverging branch of the main channel that re-enters the main channel some distance downstream. Secondary and anabranch channels can be subdivided into: *side channels, wall-based channels, distributary channels, abandoned channels, chutes, and swales* (see Technical Background Section 2.5, Floodplain-building Processes, and Glossary).

Presence of secondary channels on floodplain surfaces can convey much information to the field practitioner regarding channel processes and the potential for channel migration through lateral erosion or avulsion processes. Active secondary channels (e.g., side channels or overflow channels) are obvious locations where the active floodplain network has flowed in the recent past. Over time, these channels may be enhanced by the river system through:

- Active enlargement of channel dimensions (i.e., width or depth) through increasing vertical and lateral connectivity with the main channel; and
- Total occupation of the river in that location through avulsion (second- and third-order avulsion).

Secondary channels can also be slowly or abruptly abandoned by the active channel when:

- The main channel migrates away from the channel area;
- The channel becomes cut off at its upstream end due to wood or sediment deposition;
- The channel fills in with sediment or organic material from in-channel aggradation and/or overbank floodplain deposition of sediment (silts and sands); and
- The main channel incises into floodplain deposits resulting in reduced connectivity with the secondary channel.

Thus, secondary channels can be episodically activated and deactivated, either partially or fully through time. Over time, secondary channels can become less defined due to infilling and vegetation growth, which masks their surface distinction and the interpretation of their previous fluvial processes. In certain situations, secondary channels may also stay static in their form and processes. A static secondary channel is rare in Washington State where discharge of water, sediment and wood is often highly variable through time, creating dynamic channel evolution processes.

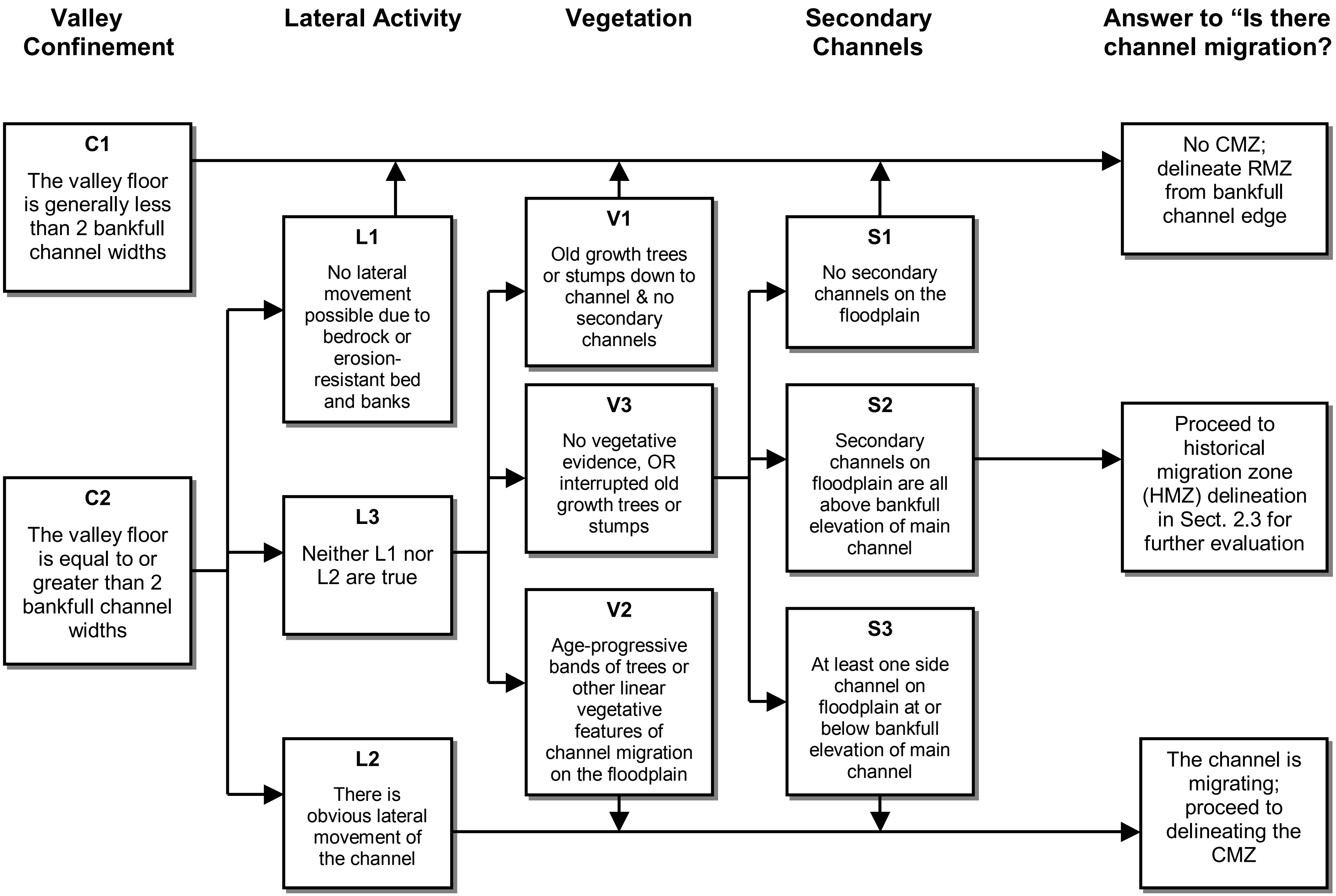
The presence of secondary channels does not alone predict the likelihood of future channel migration, nor does the absence of secondary channels on the floodplain solely indicate that channel migration by avulsion is unlikely. These features need to be assessed individually and in conjunction with other floodplain forms and processes along the segment of interest.

If there are no secondary channels of any sort on the floodplain, channel migration is unlikely. This would mean that there are no other indicators of channel migration described under the L2 or V2 evidence above. Proceed to delineating the RMZ from the bankfull edge (S1).

The channel is migrating if there are any side channels on the floodplain where the bottom of the channel is at or below the bankfull elevation of the main channel, proceed to delineating the CMZ (S3).

If there are secondary channels on the floodplain and all bed elevations of these channels lie above the bankfull elevation of the main channel, then channel migration may have occurred but cannot be determined without further evaluation. Proceed to Section 2.3 and the delineation of the historical migration zone (HMZ) for guidelines to further evaluate if historic channel migration has occurred (S2).

Flow Chart for Determining Channel Migration



2.3 Delineating the Channel Migration Zone

Once it has been determined that channel migration has historically occurred or is occurring anywhere along the channel segment that includes the proposed forest practice activity, the landowner is required to begin the RMZ at the outer edge of the channel migration zone. In addition, if the evidence for historical migration remained unclear after following the guidelines in Section 2.2, the field practitioner was instructed to use the lines of evidence for delineating the Historical Migration Zone (described below) to determine whether or not a CMZ is present. It is therefore possible to work through the delineation methods and determine that historical channel migration has not occurred and CMZ delineation is not necessary.

The following guidelines and delineation scenarios contain technical recommendations for CMZ delineation. It may be reasonable to deviate from these recommendations based on carefully developed technical analysis of the historical channel and watershed processes that control channel migration. Consulting with the DNR forest practices forester or conducting additional analysis is encouraged whenever or wherever you are confused about how to proceed with the delineation of a CMZ.

Information useful to accompany the Forest Practices Application (FPA) includes a statement describing the lines of evidence used to establish the delineation along with any analyses performed or reports generated (see **CMZ Reporting Form**).

Methods Overview

The following methods have been developed to guide CMZ delineation. The general methodology in this section defines the channel migration zone based on valley and floodplain features and channel processes. The outer edge of the channel migration zone is identified using historical map and photo analysis and/or current field evidence to predict future channel migration.

It is helpful to view the river landscape as a series of the following identifiable components that can be used collectively to define the boundaries of the CMZ (Figure 13). All zones are not necessarily present along all river segments.

1. The historical migration zone (HMZ) – The sum of all active channels over the historical period (post 1900).
2. The avulsion hazard zone (AHZ) – The area not included in the HMZ where the channel is prone to move by avulsion and if not protected would result in a potential near-term loss of riparian function and associated habitat adjacent to the stream.
3. The erosion hazard area (EHA) – The area not included in the HMZ where bank erosion from stream flow can result in a potential near-term loss of riparian function and associated habitat adjacent to the stream.
4. The disconnected migration area (DMA) – The portion of the CMZ behind a permanently maintained dike or levee.

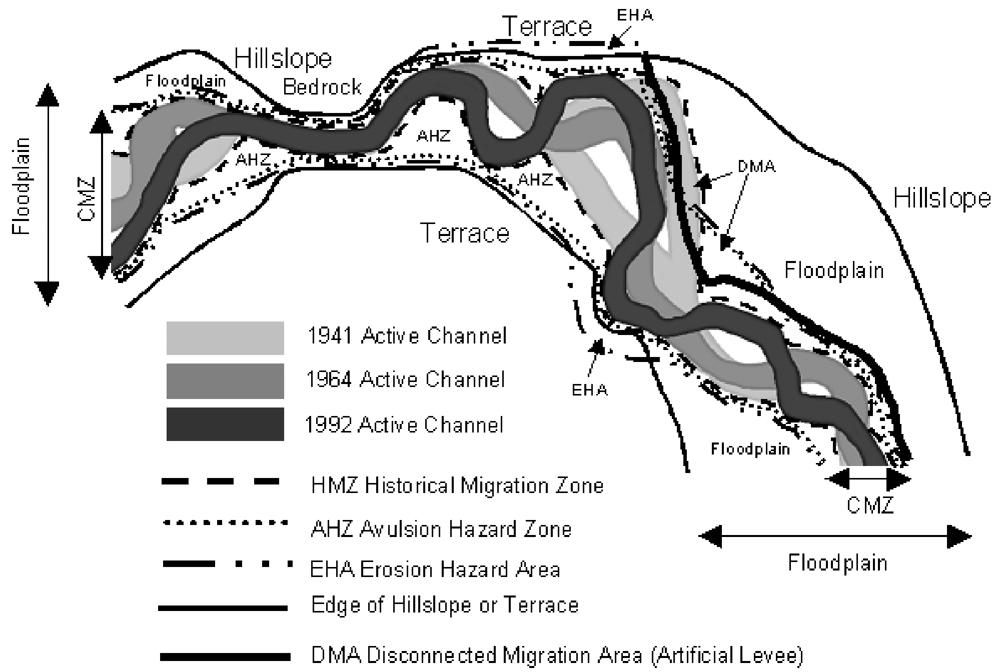


Figure 13. Example of valley and floodplain features identified and evaluated for inclusion into the CMZ delineation. <u>*All zones are not necessarily present along all river segments.*</u>

The concept of looking at the channel migration zone as a collection of these components was adapted from Rapp and Abbe (2003). All river segments with a CMZ necessarily have an HMZ; additionally, some segments have AHZ, EHA and/or DMA.

The remainder of this section presents information on channel segment delineation, delineation of the three major components of the CMZ, and identification of floodplain features outside of the CMZ. Different types or “scenarios” of channel migration situations have also been provided to facilitate CMZ delineation and illustrate the use of appropriate evidence and methods.

In delineating a CMZ, we attempt to anticipate the type and scale of large channel-changing events that may occur such as 25, 50, and 100-year flood events – the scale of events for which we have some predictive capability. Careful evaluation of field evidence will help the landowner determine the limit of channel migration over the near-term future. An understanding of general river processes may also be helpful to the landowner. To this end, a technical background section (Section 2.5) is included, and users of this manual are encouraged to become familiar with the concepts offered.

Future river channel changes (e.g., channel aggradation, altered LWD load, and channel avulsion) may bring improved understanding of local stream processes. When these changes occur, existing CMZ boundaries can be re-evaluated in the context of an entire stream segment, and the additional information gained can be applied to future forest practices. However, a lack of channel changes within a few decades after the initial delineation does not preclude the potential for channel migration in response to larger flood events or other significant watershed changes in the future. If the nature of river form and processes is well understood during the initial CMZ delineation, future adjustments to the CMZ should be minimal.

Segment-Level Delineation

The lateral extent of the channel migration zone is based on field evidence found at the channel segment scale. Although many CMZ delineations will be specific to those portions of the stream adjacent to individual forest practices activities, some or perhaps much of the evidence for the delineation may exist on the opposite bank or elsewhere in the associated channel segment. Similar to its use in watershed analysis, stream segments are lengths of stream that have similar valley confinement, discharge, channel pattern, and average valley gradient (Figure 14). Segments may vary from a few hundred feet to a couple of miles in length, and are somewhat scale-dependent such that smaller streams may have shorter segments.

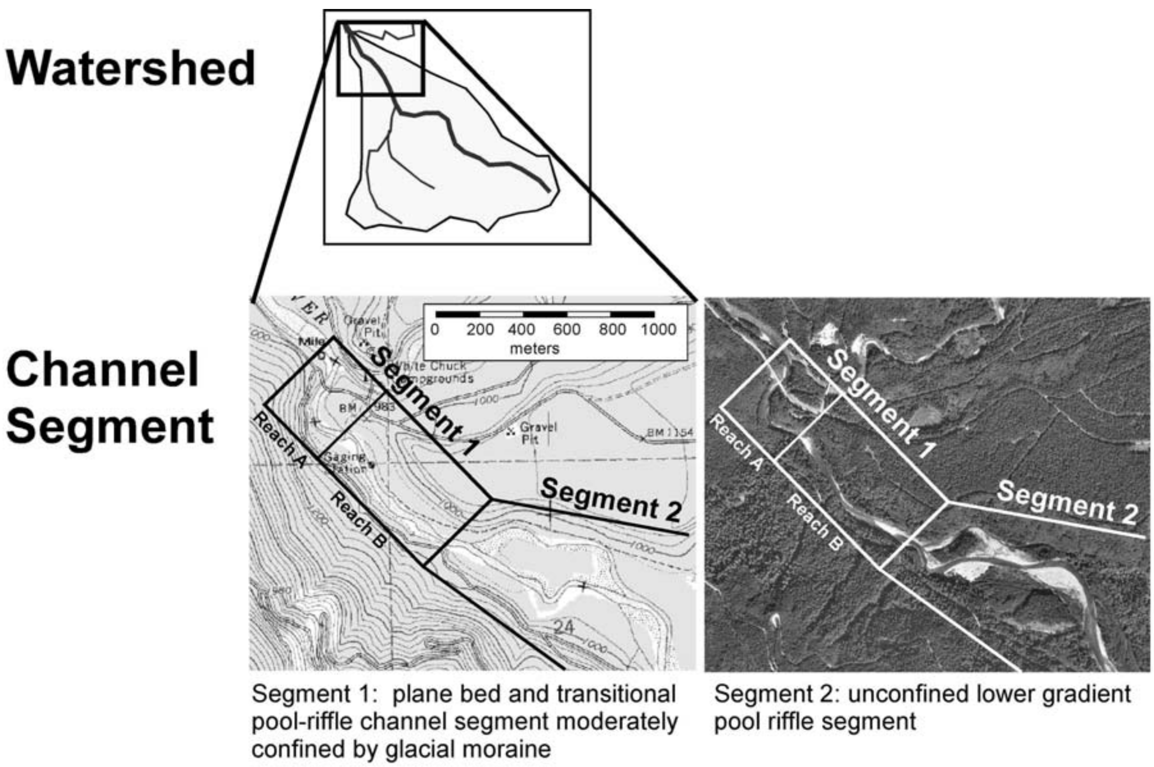


Figure 14. Example of channel hierarchy from watershed to segment to reach scale.

Identifying Segment Breaks

Stream segments are most easily identified initially from topographic maps and aerial photographs, and then field verified. Segment breaks are determined from abrupt or gradual changes in confinement, gradient, channel pattern, streamflow, or other channel or watershed characteristics as listed below:

- Confinement: A change in the valley confinement (i.e., the ratio of bankfull width (w_b) and valley width (w_v)), approximately corresponds to one of three confinement classes from a wide floodplain to a confined canyon.

Confinement class	Floodplain width
Unconfined	$w_v > 4\ w_b$
Moderately confined	$2\ w_b < w_v < 4\ w_b$
Confined	$w_v < 2\ w_b$

- Gradient: A significant change in average channel gradient, corresponding to one of the following gradient classes:
  0-0.9 % 1.0-1.9 % 2.0-3.9 % 4.0-8.0 % 8.0-20 %
- Channel pattern changes (e.g., from a straight to sinuous to braided channel, or a single-thread to anabranched channel)
- Tributary confluences, which can result in:
  - Significant streamflow discharge changes
  - Significant channel width and/or depth changes
  - Significant changes in the type and/or quantity of sediment.
- Streambed or streambank material changes (e.g., bedrock to gravel bed, cohesive to non-cohesive banks).

Advantages to delineating a CMZ for one or more segment lengths rather than a single forest practices application are:

1. At the broader scale, it is easier and more defensible to define segments of varying activity from no migration to small-scale migration to very active migration. In some large river systems, segments of active migration and those of little or no migration may alternate down the length of the river. Careful analysis of the aerial photo record and the field evidence for migration will help define these segments. Observations may lead to hypotheses about the subtle controls causing these changes. It may be difficult to defend the delineation of just two segments, one with no or only small-scale migration and one with very active migration, but this distinction may be quite defensible when alternating segments of different behaviors have been documented. Large-scale analysis of channel migration is most strongly recommended for large rivers.
2. Multiple segment analyses provide a higher level of confidence in channel migration delineation because more is understood about the river's migration behavior.
3. There may be significant cost savings in conducting a large-scale analysis. Cost savings are likely to be very significant if landowners and other cooperators conduct these analyses together.

Channel Migration Zone Components

The CMZ, as defined by forest practice rules, may or may not include all portions of the floodplain. Some floodplain surfaces may be periodically inundated, but lack the risk factors for channel shifting or bank erosion. The following terms are defined and described below for those areas included in the CMZ.

A “surface” of a floodplain is a widely used but poorly defined concept. Conceptually, a “surface” is a constant feature up and down the valley. It lies at a consistent elevation above bankfull. A discrete process at a discrete point in time has formed the surface, resulting in consistent soil development and other age indicators. Unfortunately, these conceptual “surfaces” rarely exist because processes that form floodplain surfaces are complex and often localized. Where contiguous surfaces were formed, they have often been fragmented by erosion and avulsion. Therefore, a “*surface*” is specifically defined as those individual pieces of the floodplain that share the following characteristics:

- The surface lies at a fairly consistent relationship to the bankfull channel elevation, understanding that the relationship between a given surface and bankfull elevation can vary within a segment due to irregularities on the surface and due to local flow patterns and obstructions.
- The surface displays evidence that supports fairly constant flood frequency.
- The surface supports a fairly similar plant community as influenced by water table or flooding (perched wetlands should not be included in this consideration).

It is assumed that a common process as defined above has formed the parts of a surface.

Historic Migration Zone (HMZ)

The historic migration zone (HMZ) is the sum of all active channels over the historical period, and is delineated by the outermost extent of channel locations over that time (Figure 13). This is direct evidence of where the channel has been and may be assumed to reoccupy. The historical period usually includes the time between the year 1900 and the present – the approximate time period sufficient to capture pre-timber harvest channel conditions. This time period is extended for those sites known to have been impacted by timber harvest activities prior to 1900, or where historical information such as Government Land Office maps and notes are available (http://riverhistory.ess.washington.edu/ for Puget Sound Rivers and http://pnptc.org/t-sheets.htm for Olympic Peninsula Rivers). At a minimum, the CMZ will include the HMZ except where a portion of the HMZ is behind a permanently maintained dike or levee (see Disconnected Migration Area).

The HMZ is identified based on photos, maps, and field evidence (Figure 15). Since few streams have a complete historical map and photo record or the stream may be too small to be adequately assessed from photos or maps, what historical data is available is supplemented with field evidence. When in doubt whether a surface is part of the historic migration zone, evaluate for avulsion hazard potential.

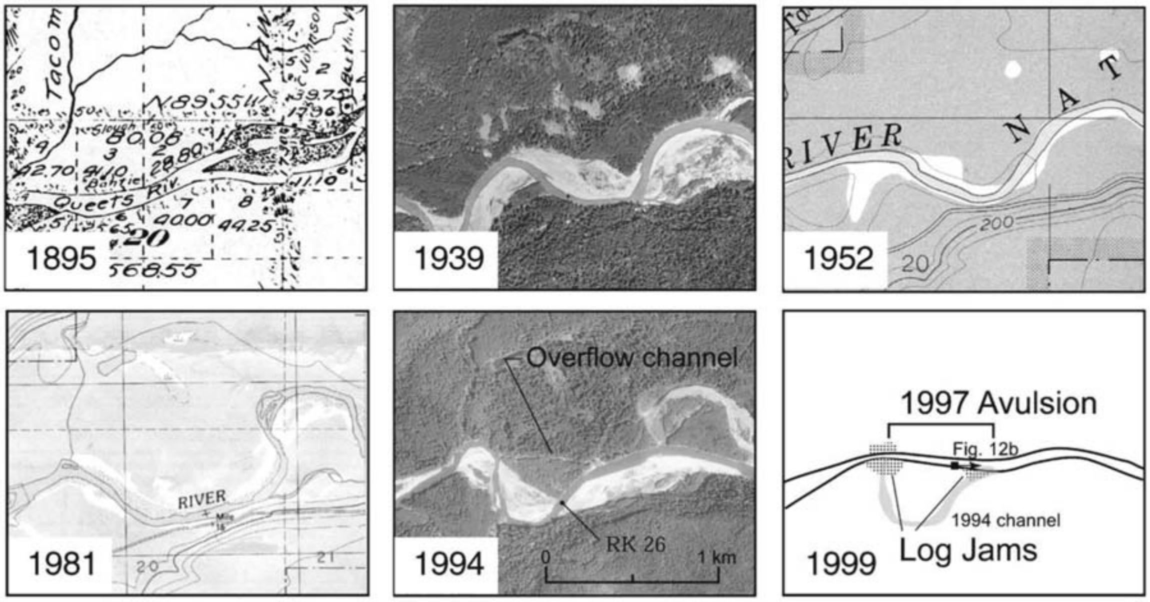


Figure 15. A sequence of historical channel maps and photos: 1895 General Land Office Survey; 1939 USGS aerial photograph; 1952 15' USGS topographic quadrangle map; 1981 7 ½' USGS topographic quadrangle map; 1994 DNR orthophoto; and a field map (modified from O'Connor et al. 2003).

In determining the historic migration zone first include the area within the active channel and any side channels. Then, if available for the segment, analyze the historic map or air photo record to determine the areas the channel has occupied in the past. Next, examine the floodplain surface(s) for channels abandoned within the historic time frame that may not be evident on the historic map or air photo record. Evidence of historic abandonment may include: lack of stumps; surficial deposits of gravel or cobble, which can be thinly covered by fine, overbank sediments or duff; plant communities that are younger than the surrounding flood plain surface; and surficial evidence of logjams. Finally, examine the surface(s) for age-progressive plant communities that indicate point bar growth during the historic time period.

Evaluating the lines of evidence during the delineation of multiple-surface floodplains requires some understanding of the recent flood history of the river. The longer the period of time since the last disturbance event, the more muted the surficial evidence for channel migration will be. In particular, evidence of bed scour may be covered in leaf litter and humus. Some coring or digging in low or topographic depressions to determine the nature and age of shallow materials may be useful.

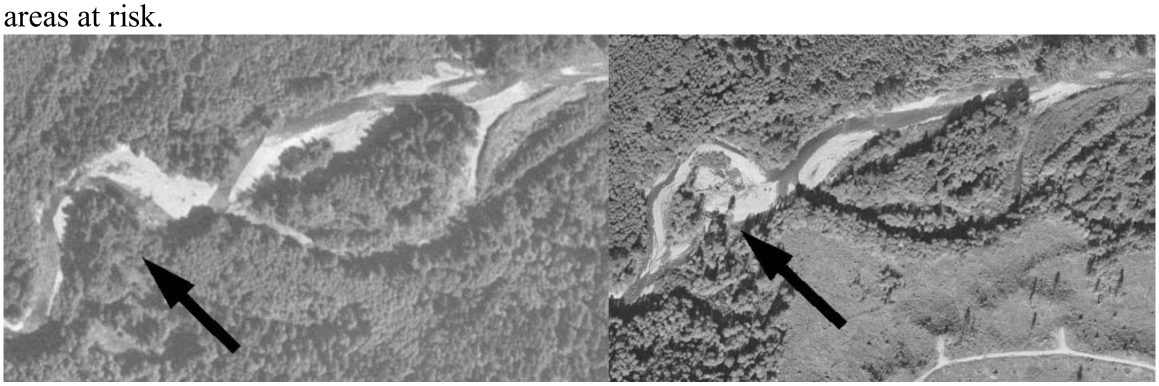
Strong field evidence of historic channel migration on a seemingly higher elevation surface may suggest a historic change in wood and/or sediment loading or channel processes that have caused the channel to downcut, and this condition can be confirmed through historical information or analysis. The reintroduction of mature wood to the stream could bring the bed elevation up to that surface in the future.

Smaller and moderately confined segments of a stream are generally closer to sediment sources and may receive large pulses of sediment that are stored for shorter time frames than sediment in large floodplains further downstream. Because these segments may aggrade and degrade rapidly, the resulting deposits may be at an anomalously high elevation above the current channel. Because these surfaces were deposited and abandoned rapidly, they may also lack any surface expression of former channel features. Where debris flow processes are active, these surfaces may be composed of debris flow deposits, and will not necessarily have the look of stream sorted sand and gravel. Buried stems of trees (no obvious rootwad) may indicate an older surface. Much of the other evidence for the HMZ will apply in these locations, even though the surface may not flood, given the current elevation of the channel.

Avulsion Hazard Zone (AHZ)

Channel *avulsions* are defined as relatively sudden and major shifts in the position of the channel to a new part of the floodplain (first-order avulsion) or sudden reoccupation of an old channel on the floodplain (second-order avulsion) (Nanson and Knighton 1996) (see Figure 38 and Section 2.5). Avulsions into floodplain deposits can occur at a variety of scales and channel sizes. Primary avulsion paths can be guided by log jams or the presence of poorly defined topographic low points along the floodplain, and secondary avulsion paths can follow better defined *secondary* or *abandoned channels* on the floodplain.

The avulsion hazard zone is the area not included in the HMZ where the active channel of a stream is prone to move to (Figure 16) and if not protected would result in a potential near-term loss of riparian function and associated habitat adjacent to the stream. The purpose of delineating avulsion hazard zones is to anticipate future shifts in channel location outside the recent historical locations. Predicting channel shifting to a new portion of the floodplain (first-order avulsion) is more challenging than predicting reoccupation of an old channel (second-order avulsion). The time frame for migrating channels to move across their floodplains varies from decades to hundreds of years; therefore, in some river systems, much older floodplain surfaces may still be subject to avulsion. The evidence and situations outlined below will help identify these floodplain areas at risk.



Figures 16a and 16b. Example of channel avulsion that occurred between two photo years.

The evidence for the avulsion hazard zone includes consideration of several situations:

1. Those floodplain surfaces extending outward from the HMZ that are of similar height to the surfaces within the HMZ, including:
   - If a surface has experienced historical avulsion within the segment, that entire surface is within the AHZ.
   - Floodplain islands stranded by historical channel avulsion.
   - The surface within the elevation of the highest channel features (gravel bars, the bulk of wood jams, mid-channel surfaces).
   - A surface beyond a flood berm that is at or below bankfull elevation.

2. There may be additional situations where the near-term risk for avulsion is significant. The relationship of a portion of the floodplain, often a meander bend, to the active channel may generate preferential avulsion paths. The possibility of such an avulsion path can be assessed in the context of knowledge of local channel behavior, knowledge of watershed condition and trends, and an assessment of the relationship of the channel to the floodplain surfaces. To assess the potential for preferential paths, the following situations need to be considered:
   - The channel has been systematically moving in one direction towards an obvious path for primary or secondary avulsion.
   - There is a continuous or intermittent linear or curvilinear depression or channel form connecting at the upstream end to the active channel that would be prone to flood in a large event.
   - Streamflow is directed at a portion of the floodplain such that floodwaters have an unimpeded, focused path.
   - The floodplain has a gradient greater than the adjacent channel, and the greater the difference the more likely avulsion will occur (Jones and Schumm 1999). Avulsions typically occur where the down valley floodplain slope is greater than (>1x) the channel slope (Bridge 2003). If the floodplain slope is 3 to 5 times greater than the channel slope, avulsion during a large flood event is probable (Bridge 2003).
   - Watershed and segment-scale evidence demonstrates that significant vertical bed aggradation due to increases in LWD or sediment (or both) is occurring or has occurred in the historical past. Evidence of the historic bed elevation should exist on any remaining adjacent surfaces, but can be buried. Specific evidence that supports the likelihood of vertical bed aggradation includes:
     - post-harvest or stream-cleaning channel degradation that has isolated historic floodplain surfaces,
     - channels with multiple floodplain surfaces that are close in elevation indicate that the channel bed elevation fluctuates,
     - in-channel sediment waves, commonly produced by concentrated landsliding, can be observed (through historic air photos or cross sectional survey records such as those at gauging stations) as channel disturbance propagated downstream over time,
     - high variability in the current channel bed elevation, and
     - the presence of islands on higher surfaces.

For additional information, see the Technical Background, Section 2.5, for a discussion of how changes in wood and sediment budgets affect channel form and migration processes,

Erosion Hazard Area (EHA)

Along some rivers there are lengths of channel where the stream is laterally eroding into a terrace or floodplain surfaces. Although the stream may not continue to erode in the same direction (it could shift back at any time) or at the same rate (the channel could reach equilibrium) over the long term, it may erode over the near term. For these stream segments, erosion rates of bank retreat and the CMZ setback distances can be calculated.

The erosion hazard area includes those areas outside of the HMZ and AHZ which are susceptible to bank erosion from stream flow and this can result in a potential near-term loss of riparian function and associated habitat adjacent to the stream (see Figure 5a and 5b). Typically, the EHA will be comprised of portions of floodplain and terrace surfaces other than those within the HMZ and AHZ. Establishing an EHA is necessary for those situations where measurable undercutting or erosion on the order of feet per year or per flood event is currently taking place. In some reaches where channels are now permanently disconnected from their floodplain due to channel degradation, the CMZ may consist solely of the EHA. However, the CMZ will not extend further than the base of the valley hillslope or other such geologic controls to lateral channel movement.

Evidence of measurable or chronic bank erosion includes:

- The channel has visibly eroded into surfaces higher than those in the HMZ and AHZ during the record of historical aerial photography.
- There are meander bends with age progressive vegetation on the point bar, indicating that erosion into the far bank has been occurring.
- There are steep or vertical, unvegetated, non-cohesive banks along higher surfaces. See Bank Erosion in Section 2.2 for additional guidance in determining if significant bank erosion is occurring if this situation exists.

The area to be included in the EHA can be calculated by averaging the historical erosion rate along the entire length of the channel segment or by calculating the erosion rate at a specific location where erosion may be concentrated.

To delineate the EHA for erosion into a terrace or non-HMZ/AHZ portion of the floodplain, the actual area(s) lost at each bank location is (are) delineated and measured using all historical aerial photographs. For segment-averaged erosion, these areas are added together. The individual or combined eroded area is divided by the length of terrace edge adjacent to the floodplain and then divided by the number of years of record used to get an average annual erosion rate. The erosion rate is then multiplied by the appropriate length of time to grow functional-size wood to get the average erosion setback along the eroding bank(s). For segment-averaged erosion, the length of eroding channel is measured along both sides of the channel, but does not include any length of channel or floodplain that abuts the valley hillslope.

$$AES = \frac{A \text{ (or } \Sigma A)}{L} \times \frac{1}{\Delta t} \times T$$

Where AES is the average erosion setback, A is the total eroded area or ΣA sum of total eroded areas over some time Δt, L is the length of eroding bank, and T is the length of time to grow functional wood.

Where the stream is eroding into floodplain surfaces or terraces, the EHA portion of the CMZ layout will protect the eroding bank edge. In addition to consideration of a CMZ, stream erosion of hillslopes and very high glacial terraces at the outside of meander bends and at the toes of deep-seated landslides are considered unstable slopes situations and are also evaluated under forest practices rules for unstable slopes (see Board Manual Section 16). As with other situations of overlapping forest practices rules, the harvest unit layout should reflect the greater of the protections.

Disconnected Migration Area (DMA)

The disconnected migration area (DMA) is the portion of the CMZ behind a permanently maintained dike or levee. The CMZ of any stream can be limited to exclude the area behind a permanent dike or levee provided these structures were constructed according to appropriate federal, state, and local requirements. As used here, a permanent dike or levee is a channel limiting structure that is either:

1. A continuous structure from valley wall or other geomorphic structure that acts as an historic or ultimate limit to lateral channel movements to valley wall or other such geomorphic structure and is constructed to a continuous elevation exceeding the 100-year flood stage (1% exceedence flow); or
2. A structure that supports a public right-of-way or conveyance route and receives regular maintenance sufficient to maintain structural integrity (Figure 17).

A dike or levee is not considered a “permanent dike or levee” if the channel limiting structure is perforated by pipes, culverts, or other drainage structures that allow for the passage of any life stage of anadromous fish and the area behind the dike or levee is below the 100-year flood level.

The Washington Department of Fish and Wildlife (WDFW) and Indian tribes can often provide assistance in evaluating the potential for seasonal fish passage and use of the floodplain, as well as details on dike permitting. Applicants should also contact local, state, federal, and tribal entities to make sure that there are no plans to remove the structure.

Figure 17. Example of a CMZ disconnected by a public right-of-way.

CMZ REPORTING FORM

Forest Practices Application/Notification
CMZ Section

To list the evidence and/or methodology used to determine the presence of a channel migration zone within the immediate vicinity of your forest practice activity.

Please enclose completed copies of the office/field forms from Board Manual Section 2, and any other additional information used to determine the presence/absence of a CMZ.

1) Is the forest practice activity adjacent to a channel migration zone?

[ ] Yes. Continue with form.
[ ] No. Delineate RMZ.

2) What was the distance of channel walked? What was the length of CMZ boundary delineated?

____

3) Please check the component(s) present in your CMZ delineation.

[ ] Historical migration zone
[ ] Avulsion hazard zone
[ ] Erosion hazard area (attach erosion rate calculation sheet)

4) Check the appropriate box(es) that best matches floodplain configuration. For additional details refer to section 2.3 in the Board Manual Section 2.

[ ] simple floodplain
[ ] simple floodplain with terraces
[ ] complex floodplain, with
  [ ] multiple surfaces
  [ ] multiple terraces
[ ] alluvial or debris fan
[ ] braided channel
[ ] unconfined meandering stream
[ ] stable sinuous channel

5) Please indicate how you marked the outer edge of the CMZ on the ground

____
____

CMZ Delineation Scenarios

The following different types or "scenarios" of channel migration are provided to facilitate CMZ delineation and the use of appropriate evidence and methods. Almost all rivers and streams with historic or active channel migration will fit into one of the following categories. Some of the delineation situations are very straightforward. Others are more complex, and it may take some additional fieldwork to be sure you have correctly identified the situation.

Read the following seven descriptions carefully and decide which situation best fits the stream segment in which you are delineating a CMZ. Each scenario includes the CMZ components likely to be included in the delineation and an example of delineation and field or analysis methods unique to those situations where appropriate.

1. *Simple floodplain abuts valley walls*

In this situation, one relatively flat floodplain surface, that is approximate in elevation to the bankfull channel, abuts the valley walls (Figures 18 and 19). There are no higher horizontal surfaces that could represent either additional floodplain or terrace. These conditions are most likely to be found where the channel is moderately confined (the valley width is approximately 2 to 4 bankfull widths – see glossary and Section 2.6).

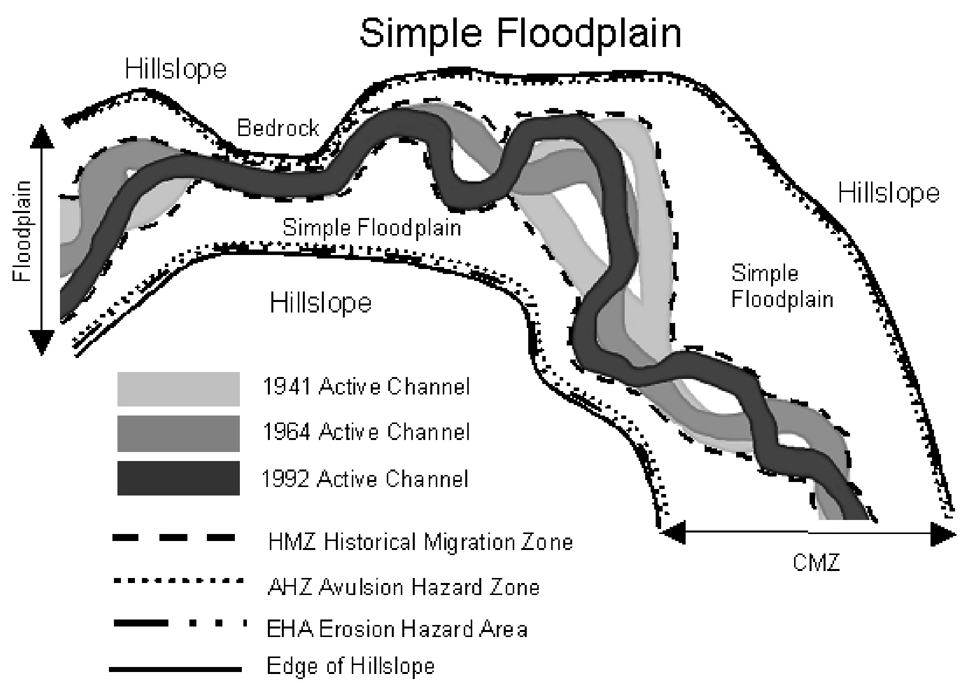


Figure 18. Illustration of simple floodplain abuts valley walls CMZ scenario in plan view.

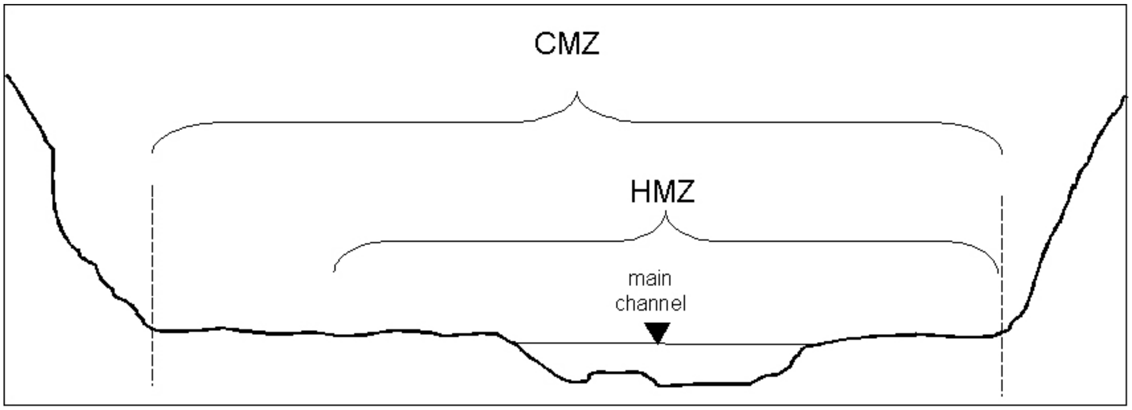


Figure 19. Cross-sectional illustration of the simple floodplain CMZ scenario.

In this situation, the simple floodplain is the channel migration zone, and will represent the historical channel locations (HMZ) in addition to any floodplain areas prone to avulsion (AHZ). The CMZ is the valley bottom, and the RMZ starts at the hillslope/valley-floor slope break. The RMZ extends up the valley wall, and its design must also protect any unstable slopes. Where migration is very active, the valley walls may be periodically undercut by the channel, creating over-steepened and unstable slopes (see Board Manual 16).

2. <u>*Simple floodplain with terraces*</u>

This situation is similar to the one above, except that the relatively flat floodplain surface, that is approximately the same elevation as the bankfull channel, abuts a terrace or terraces (Figures 20 and 21). The floodplain surface or the channel itself may intermittently abut a valley wall where there is no remaining terrace. If you are unsure that the higher surfaces are terraces, then work through the "Evidence for a terrace surface" in section 2.2 above. If you are still not sure that the higher surfaces are terraces, then assume that you have a complex floodplain with multiple surfaces and proceed to the delineation for that scenario below. This situation might be confused with the upper, narrow end of an alluvial fan (scenario 4 below) if your designated segment does not extend a sufficient distance down valley.

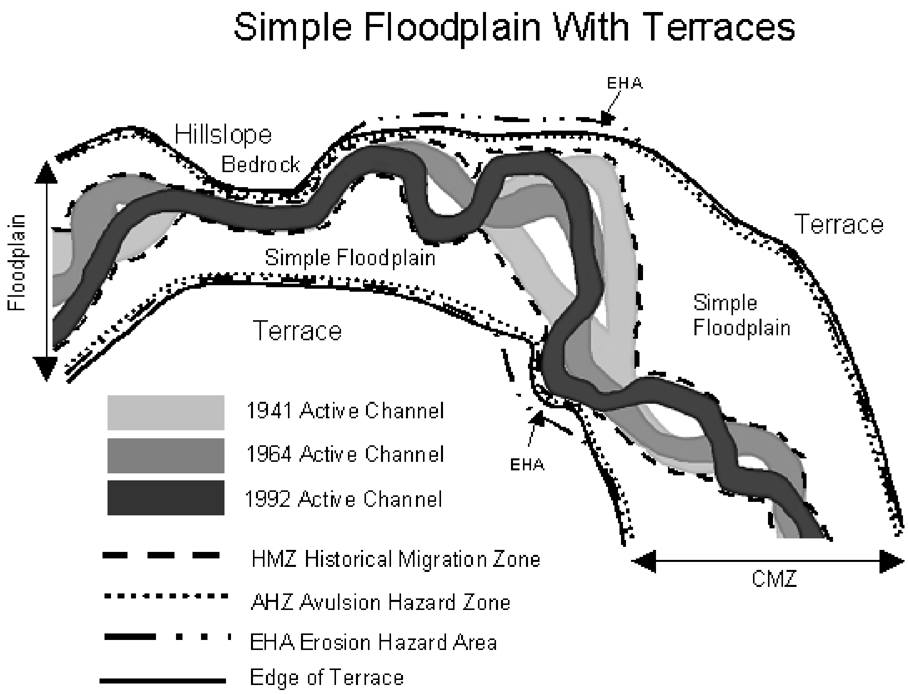


Figure 20. Illustration of the simple floodplain with terraces CMZ scenario in plan view.

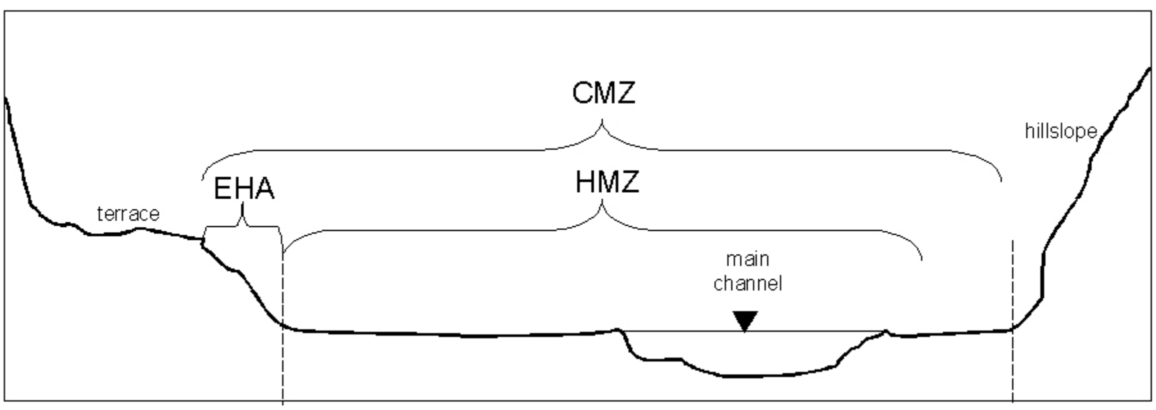


Figure 21. Cross-sectional illustration of the simple floodplain with terraces CMZ scenario.

As in the previous delineation, the entire floodplain lies within the channel migration zone, and will include the historical channel locations (HMZ) in addition to any floodplain areas prone to avulsion (AHZ). An erosion hazard area (EHA) may also be identified where rivers are still actively widening their floodplain by eroding the terraces.

3. <u>*Complex floodplain with multiple surfaces*</u>

In this situation, there are multiple surfaces of varying elevations within the floodplain (Figures 22 and 23). This situation may be caused by the interaction of sediment, debris, and water or variability in sediment and/or wood loading in the historic past, and indicates that the channel bed elevation fluctuates. Multiple floodplain surfaces may be absent where the channel abuts a terrace or valley wall within the segment. Multi-surfaced floodplains can exist for streams of varying sizes and confinements. The processes of channel migration under this scenario are primarily bank erosion and avulsion.

A helpful first step is to identify the surfaces as either terraces or floodplain by working through the “Evidence for a terrace surface” and “Evidence for a floodplain surface” criteria in section 2.2 above. If you are still uncertain, assume you are in this category.

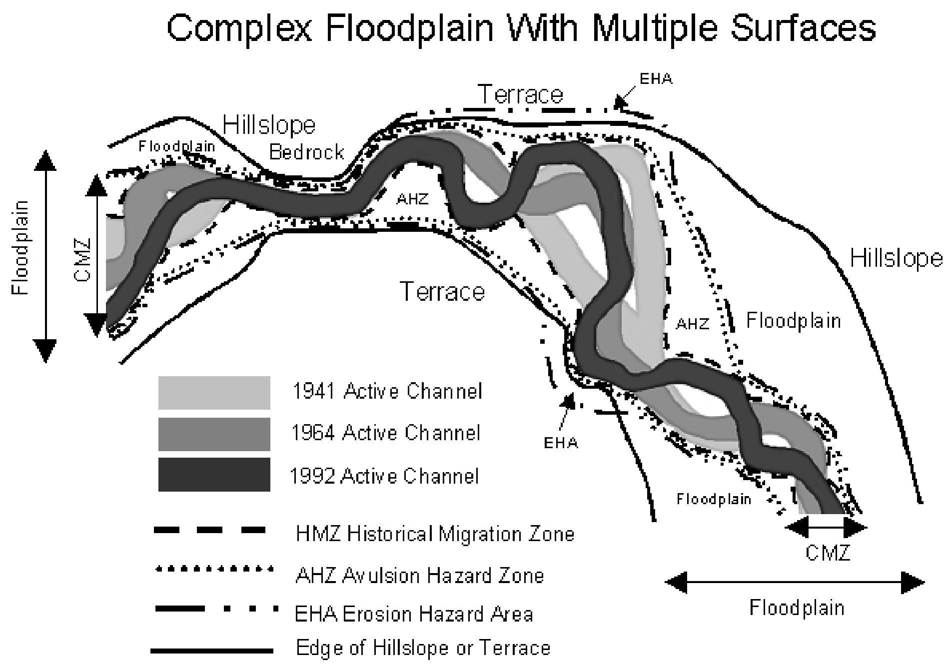


Figure 22. Illustration of the complex floodplain CMZ scenario in plan view.

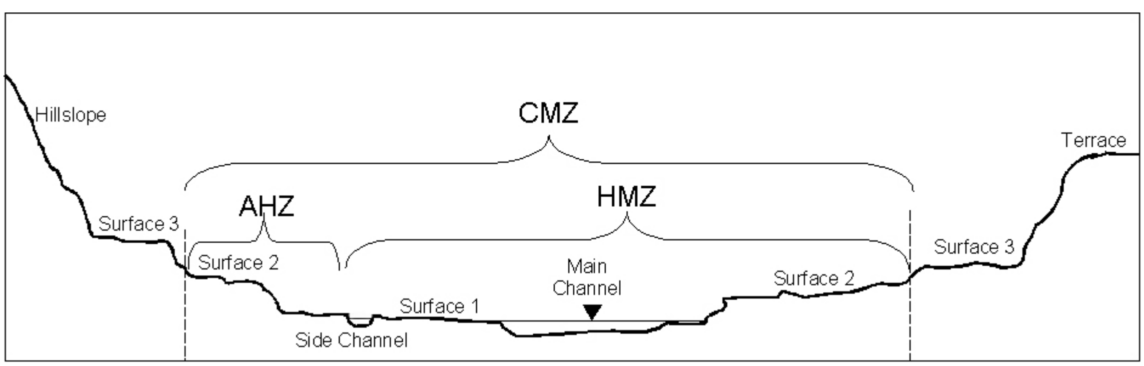


Figure 23. Cross-sectional illustration of the complex floodplain CMZ scenario.

Because of the complex floodplain features, this delineation scenario requires historical map and photo work in addition to extensive fieldwork to identify the CMZ components. The situation may require the collection of quality elevation data (e.g., cross-sectional traverses or LiDAR data for large rivers). The quality elevation data is needed to link geographically isolated surfaces to each other down the length of the reach and across the river.

Much of the criteria for each of the CMZ components above can be applied to evaluate the channel migration potential where more than one floodplain surface exists. Because multiple surfaces imply fluctuations in channel bed elevation, emphasis should be placed on evaluating evidence for vertical bed elevation changes found at the end of the AHZ Section. Refer to the Technical Background, Section 2.5, for additional information and discussion of how changes in wood and sediment budgets affect channel form and migration processes.

When you are evaluating a "surface" in order to characterize it by the CMZ criteria listed above, the entire extent of that surface along the segment must also be evaluated for evidence of channel migration potential. The CMZ delineation for these complex floodplain situations may consist solely of the HMZ or any combination of the HMZ plus AHZ and EHA. Additional analysis is encouraged.

4. *Alluvial or Debris Fans*

Alluvial fans are a unique landform in the river valley. They are cone or fan-shaped deposits of sediment and debris that accumulate immediately below a significant change in channel gradient and/or valley confinement (Figure 24). The fan shape is created as the channel moves back and forth across the gradient transition depositing sediment. It is common for the stream to form distributary channels (channels branch but do not rejoin) as water flows down the fan. On varying time scales, the channel(s) will change location on the fan, seeking a lower elevation away from where it has most recently been depositing sediment. See section 2.5, River Pattern, for more information.

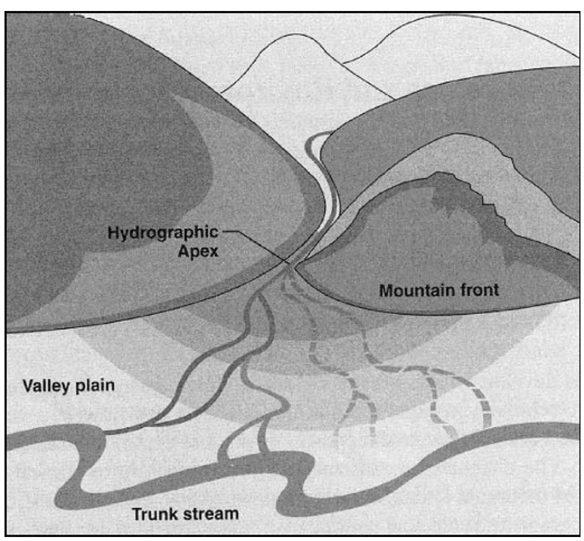


Figure 24. Illustration of the environment where alluvial fans form (National Research Council, 1996).

Technically, the term "alluvial fan" refers to those features composed of stream-sorted alluvium; however, it is also commonly used to refer to fan features built by debris flow processes or a combination of alluvial and debris flow processes. Debris flow deposits are unsorted, and debris flows will often form a berm next to the channel. Trees on a fan subject to debris flow provide a buttress effect that limits the downstream extent of debris flow deposition, which is important for protecting human life or property inadvertently in the path of such events.

Surface gradients on alluvial fans are generally between 8 and 20%, but a fan built by debris flow or mass wasting processes can have steeper slopes. Both commonly exist:

- Where a smaller channel meets a larger channel;
- Where an abrupt change from narrow to wide valley width occurs; or
- Where an abrupt change from steep to gentle channel gradient occurs.

By definition, the channels on alluvial fans migrate and are therefore subject to CMZ delineation. Alluvial fans are also identified as "sensitive sites" in WAC 222-16-010 and no timber harvest is permitted within an alluvial fan (WAC 222-30-021(2)(b)(vi) and -022(2)(b)(ii)(C)(IV)). An alluvial fan will need CMZ delineation where historical map and aerial photograph and field evidence demonstrate that channel migration has occurred or can occur due to active fan building processes upstream. Channels can be located anywhere on the fan and are best observed starting from the apex or upstream portion of the fan and following them downstream. The CMZ will generally encompass the entire fan surface because of the difficulty in predicting the future channel location.

All or some portions of the fan may no longer be subject to channel shifting if the fan-building processes have ceased or diminished. The degree of channel incision at the fan head is not a reliable indicator of the lack of channel shifting potential, as infrequent but large flood events or debris flows can rapidly fill the channel. A relict fan may have one or more small modern fans building at the downstream margin of the larger feature. In this situation, only the smaller, active fan has a CMZ. Technical expertise may be necessary to evaluate the age and frequency of fan-building processes.

A related landform is the delta, which forms distributary channels as water slows and deposits sediment upon entry into a lake or estuary.

5. *Braided Channels*

A braided stream is divided into several channels that branch and rejoin around bare or sparsely vegetated sand/gravel/cobble bars (Figure 25). Braided streams are characterized by high sediment loads relative to the transport capacity of the stream, low sinuosity, rapid shifting of bed material, and continuous shifting of the locations of the low-flow channels (Knighton 1998). The braided channel pattern is partly stage- or water level-dependent. At higher discharges the bars are flooded and the river displays a single channel. A braided stream pattern is common on streams fed by glaciers. See Section 2.5, River Pattern, for more information.

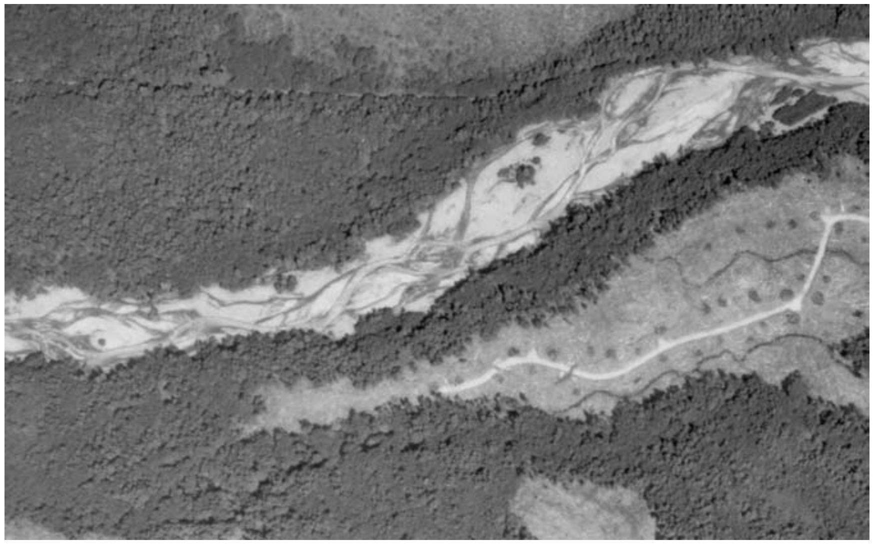


Figure 25. Example of a braided river.

Examples of some rivers known to have braided segments include the upper Quinault River, the upper Carbon River, the Mowich River, and part of the upper White River in Western Washington and the upper Wenatchee River, the north and south forks of the Touchet River, the Entiat River, and Chiwawa River in Eastern Washington.

Braided channels are each unique in their migration behavior and potential, and their delineation may require both extensive fieldwork and detailed aerial photography analysis. Where braided channels extend valley wall to valley wall, or have only small pieces of terrace or low floodplain on the valley floor, the entire valley floor is included in the CMZ and the RMZ extends up the hillslope. As in the first and second delineation scenarios, there may also be unstable slopes that require additional protection or eroding terraces that require an EHA. Braided channels with a floodplain will require the same CMZ evaluation as the complex floodplain in scenario 3 above, and expert delineation is encouraged.

6. <u>Unconfined Meandering Streams</u>

As used here (FFR 1999), unconfined, meandering streams are 5th order and larger Type S waters with bankfull widths greater than 50 feet and gradients of less than 2% with the following additional characteristics:

- The waters are sinuous, primarily single-thread channels that have a distinct meandering pattern readily observable on aerial photographs.
- Remnant side-channels and oxbow lakes often create wetland complexes within the associated channel migration zone.
- A diverse set of vegetation can grow within the associated channel migration zone including cedar, spruce, hardwoods, and wetland vegetation on wetter sites and Douglas-fir, spruce, hemlock, and true firs on drier surfaces.

A river creates these characteristics through the process of progressive bank cutting on the outside of a meander bend and subsequent deposition on the inside of the bend. A river maintaining its floodplain in this manner is generally considered in a state of dynamic equilibrium with the volume of water and sediment it carries (Knighton 1998). The elevation and basic pattern and average geometry (width, depth, and cross sectional shape) of the channel do not change (Figure 26); but the channel location migrates across the valley horizontally, and the meander pattern migrates down valley over time (Figure 27). The meander loops or bends are also subject to cut-off by avulsion (see Figure 38 and Section 2.5). Both progressive channel migration and avulsion processes create the remnant side-channels and oxbow lakes. The valleys of such rivers are generally wide relative to the size of the channel. The time frame for migrating channels to move across their floodplains varies from decades to hundreds of years. The rate of bank erosion is dependant on the scour energy of the stream (direction and magnitude) and the erodibility of the bank material.

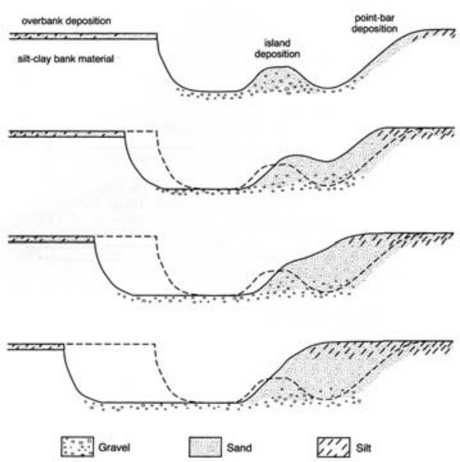


Figure 26. Progressive channel migration shown in cross section (Knighton 1998).

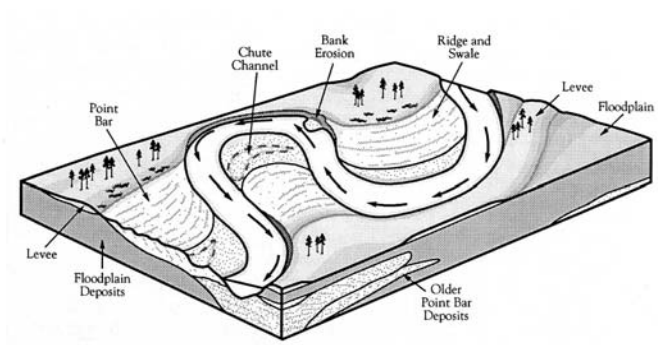


Figure 27. Progressive channel migration shown in plan view (Mount 1995).

Likely locations for rivers exhibiting this behavior include low gradient valleys below the outlets of lakes and those some distance away from primary sediment sources. The size of available sediment for transport is a factor in maintaining a single channel. There may be a few rivers in Washington where aerial photo review and field evidence show that the river migrates primarily in this manner. The methods for CMZ delineation of these stream types are described below.

For large sinuous, or meandering, rivers that are unaffected by permanent dikes or levees and show historical or photographic evidence of the channel migration processes described above, the extent of the CMZ can be determined by one of the following methods:

1. Using aerial photos to determine the amplitude of the meander wavelength described below; or
2. Evaluating the average annual bank erosion rate as described for the Erosion Hazard Area in Section 2.4 above.

As illustrated in Figure 28, the meander bends of a river have a wave pattern characterized by a general wave-length and amplitude. The amplitude of the meander bends can be used to help delineate the approximate extent of the channel migration zone (Method 1). From aerial photographs, two generally parallel lines are drawn to encompass the maximum amplitude of the meander wave and any meander cutoffs or oxbow lakes in a given stretch of river. These parallel boundaries can be roughly located in the field using landmarks identified from aerial photos to place the CMZ boundary. Changes from riparian to upland vegetation communities, geologic controls, remnant side-channels, oxbow lakes, and associated wetland complexes can be used as field indicators to help identify the extent of the meander belt. The CMZ delineated in this manner is assumed to encompass the historic migration zone, the avulsion hazard zone, and the erosion hazard zone.

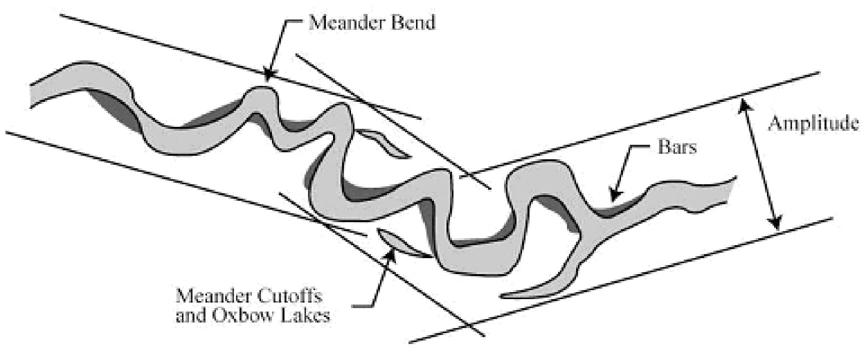


Figure 28. Method 1: CMZ equals area within amplitude of meander bends.

When using Method 1, the segment should also be evaluated for the potential for primary avulsion outside of the meander belt (see Avulsion Hazard Zone above). If avulsion outside of the meander belt has occurred historically, using a different scenario and delineation method may be necessary. If it's unclear where to draw these lines to include or exclude some meander pattern floodplain features, an expert analysis is recommended. Method 2 is advised where the river is eroding into a terrace edge or the stream has been eroding laterally across the floodplain in a single direction either throughout the entire segment, a portion of it, or at a single location.

7. <u>*Stable, Sinuous Channels*</u>

Bare or exposed banks alone are not necessarily an indicator of channel migration. Segments of rivers or streams that are unconfined, low gradient, and sinuous may be stable and may not exhibit active bank retreat or lateral migration over time if erosion or avulsion processes are inactive. Stable sinuous streams or segments have a gradient generally less than 1% and silt or clay banks. In stable stream segments, the bankfull channel position shifts negligibly over the span of the photo record. These stable reaches do not need CMZ delineation.

Included in this category are those wetland channels that have no ability to migrate because they are very low energy and transport low volumes of sediment. These streams have very low gradients (e.g., <.05%) and are narrow and deep (channel width < 3 times channel depth). Their substrate is predominately silt or fine organic particles, banks are stabilized by the roots of wetland vegetation, and >90% of the water surface is smooth. These channels are not common on forested lands except in certain low elevation, coastal plain situations (e.g., Willapa Bay). This does not include distributary channels in deltas or estuaries where the stream meets a larger water body such as a lake, river, or the ocean).

2.4 CMZ Review and Additional Analyses

Pre-application reviews by stakeholder groups can be useful in identifying important processes affecting channel migration and determining additional information necessary to delineate a channel migration zone.

An interdisciplinary team (I.D. team) is recommended for those situations that are complex or potentially controversial. An I.D. team will benefit if members have familiarity with the stream system and/or have an understanding of geomorphic and channel processes.

Additional analyses are recommended for CMZ delineations of large rivers and multiple river segments, alluvial fans, and braided channels. These analyses may include information such as a thorough review of channel behavior over the historical record, a synthesis of the watershed processes driving channel migration, a topographic analysis (channel cross sections, longitudinal profile, or LiDAR), the origin, composition, and erodibility of valley fill and features, and any additional analyses appropriate to the situation. CMZ delineation is a relatively recent concept, and no one method of analysis has been adopted or prescribed. Various geomorphic, engineering, and modeling methods can be applied to channel migration delineation (FEMA 1999).

2.5 Technical Background

Introduction

River and stream channels are constantly adjusting to changes in flow, sediment, and other debris loads. The tendency for a channel to adjust both vertically and horizontally to these variable inputs of mass can cause it to move laterally across its valley. The concept of delineating the area where the channel is prone to move, or the *channel migration zone* (CMZ), comes from an acknowledgment of these natural processes and the need to alter land use practices to accommodate them.

To aid the field practitioner in understanding and predicting the extent to which a channel may move, an overview of the processes involved in channel movement is provided here. The concepts conveyed below are helpful for understanding the definitions related to channel migration zone contained in the Forests & Fish Report (WSDNR et al. 1999), which provides the original basis for the CMZ rule. This information is also useful as a reference for complex or difficult CMZ delineations. The following technical background draws from several classic texts on river process (Leopold, Wolman, and Miller 1964; Schumm 1977; Dunne and Leopold 1978; Mount 1995; Knighton 1998; Wohl 2000) and from current work in the Pacific Northwest.

River Systems

Rivers are essentially agents of erosion and transportation, removing the water, sediment, and debris supplied to them from the land surface to the oceans or other basins. In performing this work, rivers have evolved over time to their present configuration.

The character and behavior of the stream system at any particular location reflects the net effect of a suite of independent variables that act at the landscape, local basin or channel reach scale and exert control on the dependent *channel morphology*. At the landscape scale, the combined influences of climate, geology, and land use determine the suite of processes controlling the delivery and rate of water and sediment to a stream (Knighton 1998) (Figure 29). Climate dictates seasonal precipitation patterns and temperature, thereby influencing the type of vegetation present and general runoff patterns (e.g., snowmelt versus rain-dominated). Regional geology influences topographic relief, valley morphology, types of erosional processes operating (e.g., shallow rapid soil slips, rock fall, earth flows, soil creep, or deep weathering of the rock), as well as stream chemistry.

Within a basin, differences in rock type and relief strongly influence the slope and physical characteristics along the stream channel. Land use within a basin can both directly and indirectly influence channel morphology. Direct land use effects on morphology include dams, river regulation, channelization, gravel mining, and navigation maintenance. Indirect effects on morphology include forest cutting and clearance, road building, upslope mining, agriculture and urbanization (Knighton 1998; Wohl 2000). The *flow regime*, which is defined as the magnitude, frequency, duration, timing, and rate of change of all flow events through time at a particular location within a basin (Poff et al. 1997), is the cumulative result of climate, geology, topography, and land use. All of these independent variables affect each portion of a river or stream.

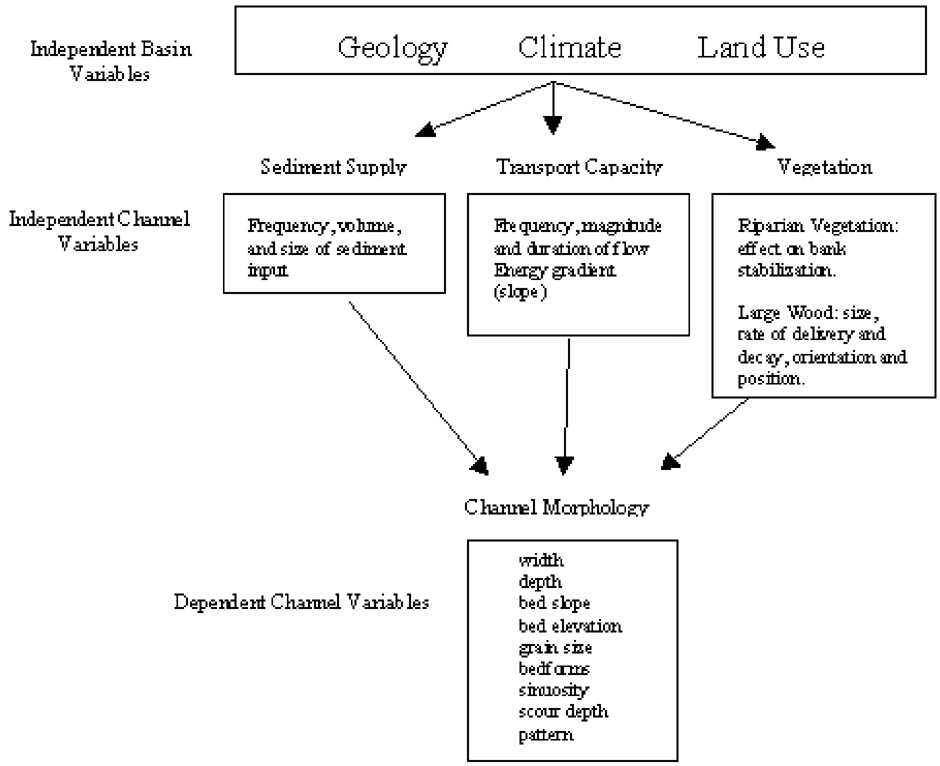


Figure 29. Diagram of independent controls on channel morphology and the dependent variables subject to change or adjustment (modified from Montgomery and Buffington 1993).

A number of concepts and classification systems have been developed to describe the river system and to help us organize our understanding of river processes. Understanding these ideas will help us predict where channels are prone to migrate within a catchment. Classically, rivers were viewed as lengthwise systems where both physical (Schumm 1977) and biological (e.g., the River Continuum Concept, Vannote et al. 1980) forms and processes change gradually downstream (e.g., Mackin 1948). In general terms, a river develops systematic downstream changes in shape and form based on increasing discharge and decreasing gradient as it transitions from the steep sediment source headwaters, through a zone dominated by transportation of sediment, to a zone of long term sediment storage and transport (Figure 30). A downstream change in physical processes also occurs as rivers become less directly coupled with hillslope water and sediment sources (Schumm 1977; Montgomery 1999; Church 2002). Applied on a broad scale, these relationships are generally true, and would suggest that channel migration is likely in floodplain valleys and mainstem rivers located at lower elevations or gradients in the system.

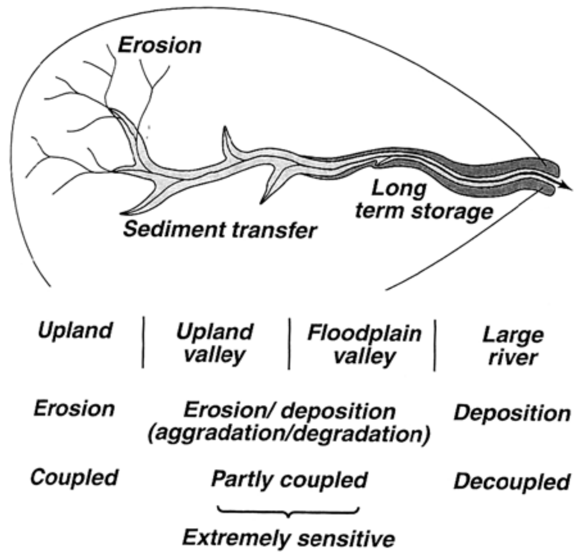


Figure 30. Watershed map showing the principal zones of sediment behavior (from Church 2002).

Given a closer look, however, most rivers will not always transition gradually and continuously downstream. Idealized, smooth, concave-up bed elevation profiles give way to stepped profiles (Figure 31). Local controls such as differences in bedrock type or structure, tributary junctions, landslides, variation in valley width, and storage of sediment and wood all influence the location and scale of these gradient steps (Rice and Church 2001; Church 2002). These local controls also interrupt the downstream fining of sediment sizes predicted by the river continuum theory and introduce variability in stream energy (Rice and Church 1998; Knighton 1999), which influences the rate of sediment accumulation and transport within a step or channel reach. Termed the "river discontinuum" theory, it predicts a patchy arrangement of channel form and response in the downstream direction (Figure 32) and suggests that channel migration may occur anywhere along the river profile (Ward and Stanford 1983, 1995; Ward et al. 2002; Poole 2002).

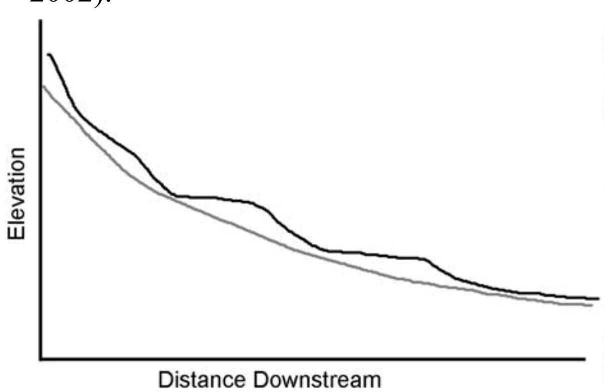


Figure 31. Comparison of an idealized river (gray line) to the more realistic profile (black line) from headwaters to mouth.

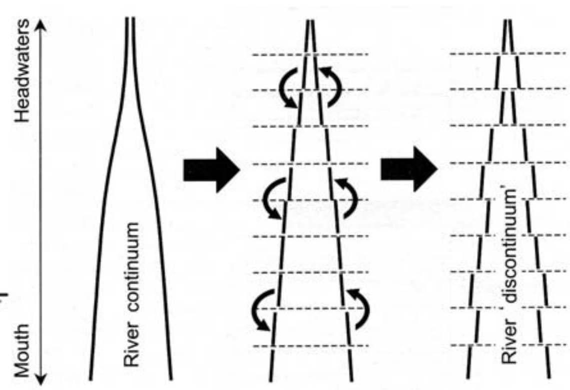


Figure 32. Illustration of different conceptual models of how rivers change in the downstream direction (Poole, 2002).

Despite their general lower elevation and gradient locations, floodplain reaches containing alluvial deposits of various scales can exist throughout a river system. The river network consists of alternating reaches with variable gradient and valley width (Figure 33). In reaches where gradient diminishes and valley width increases, sediment and organic material deposition can lead to channel adjustment and migration. Lateral channel migration through these valleys provides a mechanism of sediment exchange and serves to create and maintain these floodplain deposits over time.

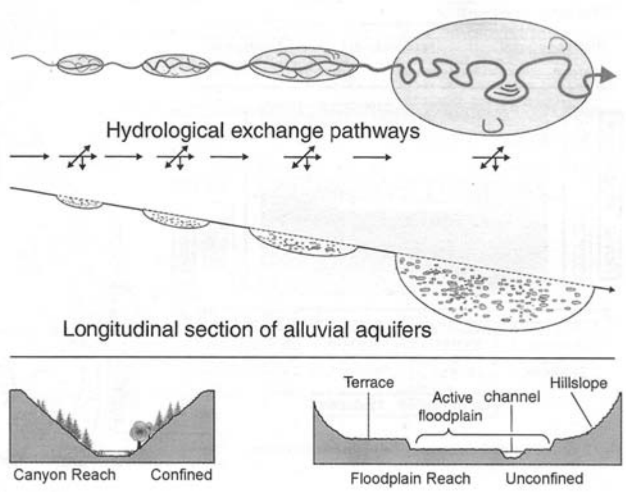


Figure 33. The channel network shown as a series of confined and unconfined reaches. Additionally, hydrologic exchange pathways are shown for the longitudinal, lateral and vertical dimensions (from Ward et al. 2002).

River systems are described in four dimensions: three spatial planes (cross-section, long profile, and planview) and time (Figure 34). Channel geometry (width and depth) and confinement are derived from cross-sections and used to evaluate the area through which water and sediment are moving. Channel gradient (potential energy) is illustrated in profile and channel patterns are conveyed in planview. Changes occur in each of these planes with every flow event that alters the channel bed or banks.

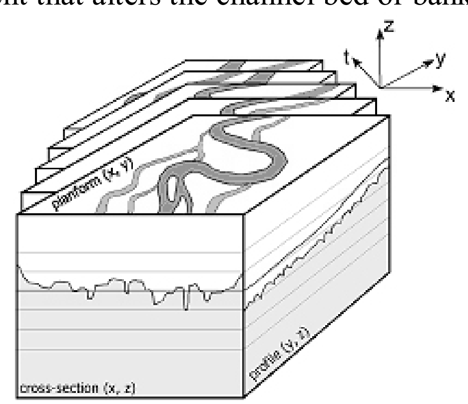


Figure 34. The four dimensions typically used to describe the morphology of a river include physical space (x, y, z) and time (t). Three two-dimensional planes are: 1) cross-section (x, z), 2) long profile (y, z), and 3) planview (x, y). The x-axis extends perpendicular to the river channel and its valley, the y-axis parallels the valley, and the z-axis is vertical.

Schumm (1985) defines three major categories of stream channels: bedrock, semi-controlled, and alluvial. Bedrock channels are composed of and controlled by bedrock. This category of channel is generally stable over time and does not change its position unless there are weak sections of bedrock that allow the channel to shift laterally. A channel may also be non-alluvial when materials that were not transported by the river under current conditions bound it. Such examples include channels that are deeply incised into hillslope or glacial deposits. Semi-controlled channels have local controls that resist channel movement. Local controls can be areas of bedrock, resistant alluvium, or large wood and logjams (Schumm 1985; Abbe and Montgomery 2003). *Alluvial* channels are formed in and flow through the sediment transported by the river, referred to as alluvium. Since alluvial channels are shaped by the volume of water and debris load they carry, they are also self-adjusting to alterations that change the timing and volume of flow, wood, and sediment load. It is the alluvial channels that have the capacity to build floodplains and migrate laterally.

The relationship between a channel and the valley through which it flows is fundamental to channel migration. The degree to which a channel is deflected by the valley walls or by resistant terraces is known as *confinement* (Kellerhals et al. 1976). Many applied scientists use some description of valley confinement to define hillslope constraint on channel processes. Although confinement is often reported as the ratio of average valley width to average channel width (e.g. Cupp 1989), little empirical data exists to support a numerical interpretation of this relationship. However, it remains a useful relative measure. Rivers and streams unconfined by hillslopes can also be artificially constrained by dikes or road grades constructed on the floodplain or in the channel itself.

In contrast to channel confinement, channel *entrenchment* is the relationship between the channel and the relatively flat surfaces on the valley floor that may be prone to flooding at some maximum stream discharge (Galay et al. 1973; Kellerhals et al. 1976). A qualitative definition of entrenchment is the vertical containment of a river and the degree to which it is incised within a valley floor (Kellerhals et al. 1972). Although attempts have been made to quantify entrenchment as the ratio of average *flood-prone width* to the average channel bankfull width within a reach (e.g. Rosgen 1994), little empirical data exists to support precise numerical classifications. Flood-prone width refers to the width of the stream at some maximum stream discharge (Galay et al. 1973) (Figure 35). Channel entrenchment can occur in response to natural processes (e.g., tectonic uplift) or human disturbance (e.g., channel clearing and straightening, harvest and clearing of floodplain forests, urbanization, upstream impoundments).

The Floodplain

The river *floodplain* is defined as the relatively flat area or berm adjoining a river channel and actively constructed by the river in the present climate by a combination of progressive lateral migration, channel creation and abandonment, and overbank sediment deposition from periodic inundation. Floodplain inundation can result from any combination of overbank river and tributary water at high discharge, hillslope runoff, groundwater, and direct precipitation. Floodplains may not be uniform or homogeneous flat surfaces, and can consist of irregular or multiple surfaces at different elevations that reflect vertical differences in the channel bed resulting from reach scale scour or fill and changes in flow regime, sediment supply and wood loading.

The height at which the channel overflows its banks is called the *bankfull stage* and corresponds approximately to the discharge at which the channel characteristics are maintained. The floodplain is, by definition, the valley level corresponding to the bankfull stage, or slightly less than bankfull if natural *levees* exist. Areas outside the bankfull channel (i.e., floodplain) are areas of short- or long-term sediment storage. The relatively flat valley bottom of the floodplain composed of river alluvium is the most direct evidence of lateral migration (Dunne and Leopold 1978). Because channels are rarely in equilibrium and constantly undergoing adjustment (particularly in areas with historic forest clearing (Wolman and Leopold 1957, Lisle and Napolitano 1998; Wohl 2000), floodplain and bankfull elevations change and are therefore not constant through time.

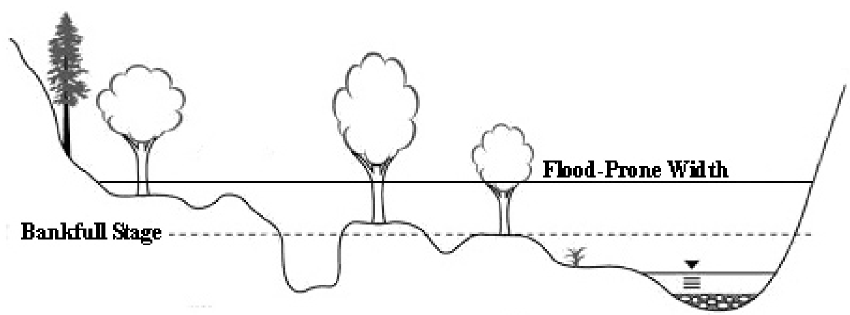


Figure 35. Simplified valley cross-section of alluvial valley bottom illustrating the effects of various stages on channel width.

Field determination of bankfull stage is difficult when the floodplain is narrow or not flat or well defined. The difficulty is greater in foothills and mountains (Dunne and Leopold 1978), because processes in addition to the floodplain building process described below are operating (see Part 1 on Bankfull Channel Features and the section below on the Magnitude and Frequency of Channel-forming Events). The bankfull concept was developed for alluvial channels and does not apply to bedrock bounded or confined channels.

Floodplain-building Processes

Floodplains represent areas where river borne sediments (both bedload and suspended sediments) are stored at least temporally within the valley. Floodplains play an important role in conveying high flows, diffusing flood levels downstream, and exchanging organic and inorganic material. Dominant floodplain building processes include overbank deposition of sediment (both fine or coarse), bar deposits in actively meandering rivers, and residual deposits associated with channel creation and abandonment. The sediment and debris stored in a floodplain are eventually re-introduced to the channel at varying time scales and conveyed further downstream. Floodplain river systems often have multiple types of interacting *channels*, which aid in floodplain building processes and the conveyance of water longitudinally and laterally. *Secondary channels* carry water (intermittently or perennially in time; continuously or interrupted in space) away from, away from and back into, or along the main channel. *Anabranch* channels are the most common form of secondary channel, which are diverging branches of the main channel that reenter the main channel some distance downstream. Secondary and anabranch channels can be subdivided into: *side channels, wall-based channels, distributary channels, abandoned channels, overflow channels, chutes, and swales*.

A river maintaining a floodplain through the process of progressive bank cutting on the outside of a meander bend and subsequent deposition on the inside of the bend (Figures 36 and 37) is considered in a state of dynamic equilibrium with the volume of water and sediment it carries (Knighton 1998). The elevation and basic pattern and average geometry (width, depth, and cross sectional shape) of the channel do not change; but the channel location migrates across the valley horizontally, and the meander pattern migrates down valley over time. However, this process can be short circuited by dramatic shifts in the position of the channel through avulsions.

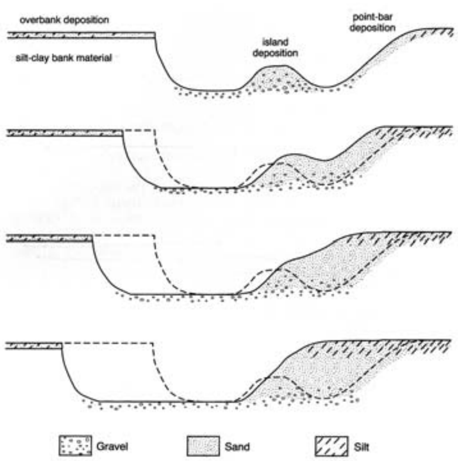


Figure 36. Progressive channel migration shown in cross section (Knighton 1998).

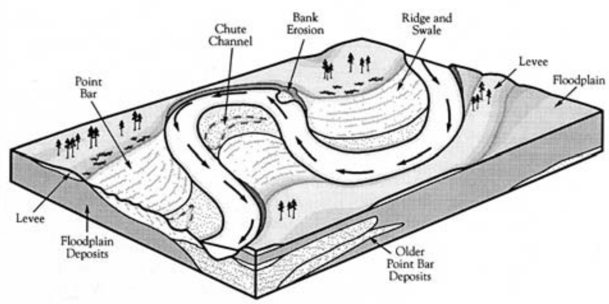


Figure 37. Progressive channel migration shown in planview (Mount 1995).

Channel *avulsions* are defined as relatively sudden and major shifts in the position of the channel to a new part of the floodplain (first-order avulsion) or sudden reoccupation of an old channel on the floodplain (second-order avulsion) or relatively minor switching of channels within a braid train or other active channels (third-order avulsion) (Nanson and Knighton 1996). Avulsions onto floodplain deposits can occur at a variety of scales and channel sizes. Primary avulsions paths can be guided by the presence of poorly defined topographic low points along the floodplain, and secondary avulsion paths can follow better defined *secondary* or *abandoned channels* on the floodplain. The shifting of the main channel into an active *side channel* or braid (third-order avulsion) is not considered a classic channel avulsion per se, but rather represents the typical channel-switching phenomenon of *anabranching* rivers as defined by Nanson and Knighton (1996) (see River Pattern section below).

Avulsions occur when the channel capacity to convey water, sediment, and wood is reduced. Avulsions can be caused by any combination of a downstream decrease in the main channel slope, an increase in slope down-valley along the floodplain as compared to the channel slope, local sediment build up in the channel called *aggradation*, wood debris jam formations, ice jams in colder climates, vegetation encroachment, hydrologic change in peak discharge, and/or stream capture from adjacent or secondary channels (Jones and Schumm 1999; Bridge 2003). Typically, as a channel becomes more sinuous as it actively meanders, the channel length increases (relative to the same down valley distance) and the slope decreases, slowing the water, which favors sediment deposition and higher water surface elevations. This condition increases the potential energy for eroding a new, steeper, shorter, and less resistant course through a floodplain meander deposit, resulting in a meander *chute* (or *neck*) *cut-off* or an avulsion (Figure 38). These processes can be aided by stream capture from the headward erosion of secondary channels draining the floodplain (Thompson 2003) and large woody debris deposits in the old main channel (Abbe and Montgomery 2003).

Empirically, avulsions or cut-offs typically occur when the floodplain slope (i.e., potential avulsion path) is greater than the channel slope ($S_f/S_c>1$) (Jones and Schumm 1999; Bridge 2003), the ratio of the bend radius of curvature to channel bankfull width is less than two ($r_c/w<2$) (Lewis and Lewin 1983; Knighton 1998), or the channel *sinuosity* (channel thalweg length vs. straight-line valley length) is greater than one and a half ($L_c/L_v>1.5$) (Leopold et al. 1964). The occurrence of an avulsion also obviously depends on the prerequisite ratio of a high discharge event above a threshold discharge for avulsion ($Q_{max}/Q_{threshold}$) (Bridge 2003) or other complicating factors such bed *aggradation* or wood debris jam formations (Jones and Schumm 1999; Bridge 2003).

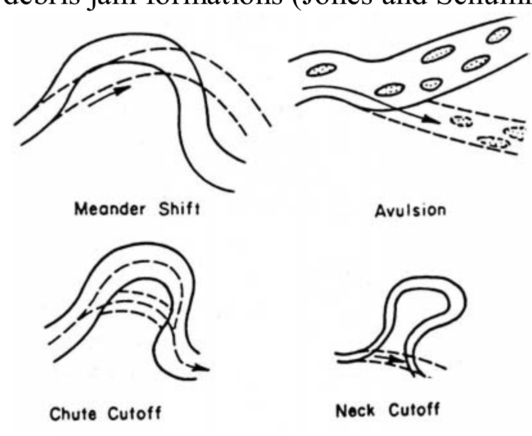


Figure 38. Types of channel changes (Modified from Schumm 1985). Solid lines indicate pre-change channel position. Dashed lines indicate post-change channel position.

Role of Wood in Streams

> *"Gravel, sand, and silt collect in the dead water, behind the drift piles, strengthening them and preventing the river from returning to its original bed. Evidences of this action are plentiful, and, in the narrow valley of the upper*

> *reaches, show that the river has been forced from the hills on one side to those of the other, a distance of ½ mile (0.81 km) or more, and the original bed has become overgrown with very heavy timber."* From a description of the White River, near Auburn, Washington in the early 1900s (Wolff 1916).

Wood debris can play a significant role in channel migration throughout a fluvial network from headwater bedrock channels (e.g., Montgomery et al. 1996, Massong and Montgomery 2000) to large alluvial rivers (Abbe and Montgomery 2003; Lancaster et al. 2001; O'Connor et al. 2003). The majority of streams and rivers are depleted in wood debris, and historic conditions may not reflect conditions associated with intact, mature riparian forests (e.g., Maser and Sedell 1994).

Wood debris (i.e., branches, tree trunks with and without root mass) is an important element of the solid material introduced to rivers. Just like the sediment load of a river, wood debris ranges widely in its physical characteristics such as size, shape and density. Generally the larger pieces of wood debris tend to be more stable and become a significant factor increasing the frictional resistance that flow encounters (e.g., Shields and Gippel 1995, Gippel et al. 1996, Brooks and Brierley 2003). Wood debris, either as individual snags or accumulations (i.e., logjams), often creates obstructions impeding flow and sediment transport and thereby altering channel morphology. By dissipating energy through a general increase in channel roughness or directly impounding flow, wood effectively reduces the sediment transport capacity of the channel and traps sediment and other wood that would have otherwise passed through the channel. The resulting sediment storage upstream of wood accumulations raises the channel bed elevation and increases the frequency of overbank flow and the probability of a channel avulsion (e.g., Lisle 1995; Hogan et al. 1998; Lancaster et al. 2001; Abbe et al. 2003). New channels develop where flows find an unobstructed path around the wood obstruction. This process can occur from steep headwater channels (e.g., Massong and Montgomery 2000) to large rivers (e.g., Sedell and Luchessa 1982, Triska 1984, Abbe and Montgomery 1996, 2003). Wood accumulations impose a strong influence on vertical (profile) and lateral (planform) migration of streams and rivers. Logjams can raise a channel several meters and move a river from one side of its valley to another, including large rivers (Abbe 2000; Abbe and Montgomery 1996, 2003; O'Conner et al. 2003).

Other Valley Forming Processes

In mountain valleys subject to recurrent *debris flows*, debris flow deposits form the valley floor in many reaches. The defined stream channels carved in these deposits are impermanent, since subsequent floods may dam or divert or greatly enlarge them. Where such debris flows are important, levees, berms, or terraces may be distinguished and even ascribed to particular flood years. However, a floodplain, as defined above and having a constant frequency of overflow, cannot be identified or does not exist (adapted from Dunne and Leopold 1978).

In the Pacific Northwest, rivers may also occupy valleys formed by quiescent processes from former continental or alpine glaciation or volcanic mudflows (Booth et al. 2003). A river or stream that appears too small to have eroded the valley in which it occupies is called an *underfit stream* (Knighton 1998). An example of an underfit stream is the White River, which flows through a valley produced by multiple glaciations combined with periodic deposition of volcanic related mudflows (*lahars*) and debris flows originating from the Mount Rainier volcano (Collins et al. 2003).

Alluvial fans are a unique landform in the river valley. They are cone- or fan-shaped deposits of sediment and debris that accumulate immediately below a significant change in channel gradient and/or valley confinement (Figure 39). The fan shape is created as the channel moves back and forth across the gradient transition depositing sediment. Technically, the term refers to those features composed of sediment deposited by running water; however, it is commonly used to refer to those features also built by debris flows that simply overflow the channel and spread out onto the fan surface. Debris flow deposits can be later reworked by the stream and deposited further down the fan surface. Generally, a gently sloping fan will be alluvial, and a fan built by debris flow or mass wasting processes will have steeper sides. Both commonly exist:

- Where a smaller channel meets a larger channel;
- Where an abrupt change from narrow to wide valley width occurs; or
- Where an abrupt change from steep to gentle channel gradient occurs.

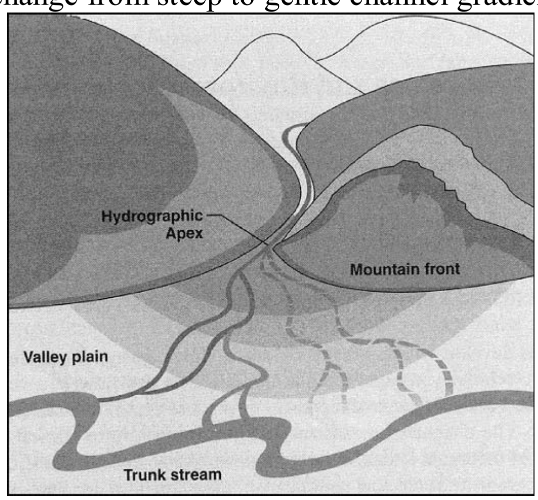


Figure 39. Idealized alluvial fan environment. National Research Council. (1996)

All or some portions of the fan may no longer be subject to channel shifting if the fan-building processes have ceased or diminished. The degree of channel incision at the fan head is not a reliable indicator of the lack of channel shifting potential, as infrequent but large flood events or debris flows can rapidly fill the channel.

Magnitude and Frequency of Channel-forming Events

River channel form is a product of all flow and sediment transporting events and the sequence of those events through time. Fluvial systems also have memory for past events, as partially displayed in the current channel form. Of the total sediment load, bed-load transport has the greatest effect on channel form (Knighton 1998). While all flow events cumulatively do influence current channel form, not all events produce the same effect or occur at the same *flood frequency*. This has lead to the theory that a *dominant* discharge controls the gross channel geometry.

In many alluvial streams, channel size (i.e., width, depth) is established by flood events that occur frequently, which over time accomplish the most work and move the greatest volume of sediment (Wolman and Miller 1960). While larger flood events, those that occur on average every 50 years, do more work and move more material than small events that occur on average every 2 years, the cumulative work and sediment movement from twenty-five '2-year' floods over fifty years is usually far greater than the one '50-year' flood. Thus, the dominant discharge that may control gross channel form is related to the *effective* discharge, which over the long term, transports more bed-load sediment than any other flow (Knighton 1998). The dominant and effective discharges for bedload have been related to flow events that just fill the channel, or the bankfull flow, for alluvial systems in humid climates. The bankfull flow represents a discharge that is reached in most years (e.g., every 1-2 years) in undisturbed watersheds in humid climates (Leopold, Wolman, and Miller 1964).

However, regionally and world wide, there is great variability among the frequency in flows that just fill the banks of the channel, especially in mountainous or arid terrain and human modified environments. The bankfull discharge may not occur frequently nor be the most effective discharge. In addition, the bankfull channel cannot always be well defined in the field. In streams with highly variable flow regimes or resistant channel boundaries (e.g., smaller, higher elevation drainage basins) (Gustard 1994), high-magnitude, low frequency events may dominate channel form and have lasting effects (Knighton 1998).

As land managers, we desire to predict the conditions that will cause specific channel changes. Land use can affect the hydrologic cycle by reducing infiltration capacity, changing the amount and effectiveness of vegetation cover, changing the timing and volume of runoff, and changing channel bed roughness and thus water velocity in channels and in overland flows. These result in changes in the volume of storm runoff and peak discharge. Such changes may be expected to result from a variety of land-use alterations, such as urbanization, grazing, agriculture, forest removal, and others. Increases in the magnitude and frequency of flow and flood pulse events can translate into alterations in the channel morphology and pattern (see Channel Adjustment below). This is especially true for common flood events such as the effective discharge. While land use may change the magnitude and frequency of extreme flood events, data records are of insufficient length to correctly quantify these changes. However, data are sufficient to quantify changes in high frequency flood events such as the effective discharge, which may have the greatest effect on channel form.

Obvious flow regime alterations occur following urbanization (e.g., Hollis 1975; Booth 1990; Booth and Jackson 1997). Impacts in forested regions have also been well studied but are a subject of much debate, especially regarding low frequency extreme events. However, it is clear that the removal of the forested canopy and/or the associated presence of a road network can alter water production. Annual water yield typically increases for some time following the reduction of vegetation cover (Bosch and Hewlett 1982; Stednick 1996). Furthermore, common peak flow events within the frequency range of the effective discharge of bedload (i.e., 0.5- to 2-year recurrence interval) increase following forest harvest and road building in small catchments (Jones and Grant 1996; Thomas and Megahan 1998; Lewis et al. 2001; Jones and Post 2004). The cumulative effects of hydrologic alterations within large watersheds are relatively unknown and undocumented.

The same factors affecting surface runoff will also tend to change sediment load. Channel response to large sediment inputs depends on channel size, position of the receiving reach within the drainage network, the quantity and size of sediment, and the characteristics of the riparian zone (Hogan et al. 1998).

Channel Adjustment

Channels are constantly adjusting to changes in the timing and volume of flow and sediment, and to the characteristics and supply of wood. Channels can adjust to changes in the rate of flow, sediment, and wood through changes in channel geometry (width, depth, and slope), channel pattern, and bed texture (grain size and bed form). Table 1 summarizes the general response in channel geometry and pattern based on changes in sediment and/or stream flow and wood debris. The time scale of responses in the dependent factors to changes in independent factors is variable. Width and depth can respond to changes within a year, while adjustment in river slope and meander wavelength may take decades to centuries (Knighton 1998). Whether the adjustment is small and incremental or episodic depends on the relative size or magnitude of the change.

Abrupt episodes of stream adjustment can occur as significant thresholds are crossed (e.g., Lisle 1982). An event such as a large flood or disturbance can dramatically reshape the floodplain and increase channel width. Climate change (geologic time scale) or a change in watershed condition by fire, timber harvest, grazing, urbanization, vegetative recovery, or direct channel manipulation (planning level time scale) may cause the river to change bed elevation either downward (*degradation*) or upward (*aggradation*). The stream will then build a new level of floodplain appropriate to the new bed elevation. These lateral and vertical adjustments in channel form over time, along with changes in channel pattern *(see below)*, are called *channel evolution*.

Table 1. Generalized adjustment in stream geometry and pattern based on changes in flow and sediment discharge (modified from Kellerhals and Church 1989, and Chang 1988) and changes in large woody debris.

Changes in Independent Factors	**Dependent or Adjustable Factors**				
	Channel Geometry			Channel Pattern	
	Width[1]	Depth	Slope	Sinuosity	Meander Wavelength
Water discharge increases alone (e.g., forest harvest)	↑	↑	↓	↓	↑
Water discharge decreases alone (e.g., water supply diversion)	↓	↓	↑	↑	↓
Sediment discharge increases alone (e.g., road building on unstable slopes)	↑	↓	↓	↓	↑
Sediment discharge decreases alone (e.g., road & harvest restrictions)	↓	↑	↑	↑	↓
Water and sediment discharge both increase (e.g., response to large storm event)	↑	?	?	↓	↑
Water and sediment discharge both decrease (e.g., downstream of a reservoir)	↓	?	?	↑	↓
Water increases and sediment decreases (e.g., climate change toward a more humid pattern)	↑↓	↑	↓	↑	?
Water decreases and sediment increases (e.g., water supply diversion plus road building and harvest)	↑↓	?	↑	↓	?
Decreased large wood debris (e.g., riparian harvest)	↑↓	↑↓	↑	↓	↑
Increased large wood debris	↑↓	↑↓	↓	↑	↓

[1] Non-cohesive bank material (↑ = Increase; ↓ = Decrease; ↑↓ = Either increase or decrease or both; ? = Indeterminate)

Conceptual channel evolution models have been created to display typical channel adjustment following channel disturbance. Simon and Hupp (1986) developed a model for channel incision and vertical channel change (Figure 40). Once disturbed, a channel may proceed through a cycle of channel degradation and incision, bank failure and widening, aggradation, and re-creation of a floodplain and quasi-equilibrium channel form (Simon and Hupp 1987, 1992 and Simon 1994). Once disturbed, the channel bed and associated floodplain may or may not return to initial bed elevations. However, if disturbed, stream channels will tend to return approximately to their previous state (e.g., pattern and size) once the perturbation is damped down (Knighton 1984) (Figure 40).

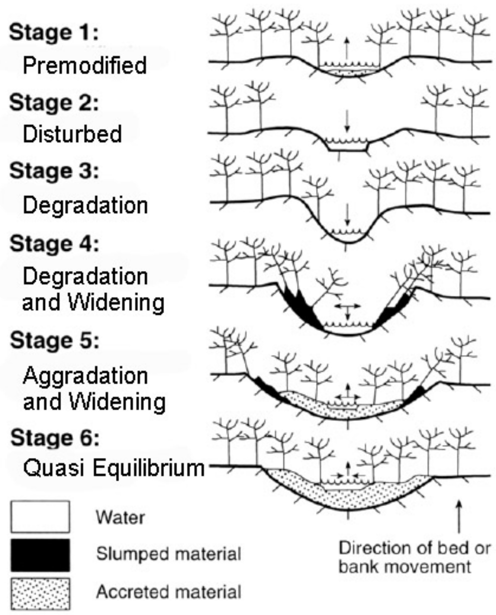


Figure 40. Illustration of channel incision and vertical channel change over time (modified from Simon and Hupp 1986).

When a stream down-cuts or lowers its bed elevation (i.e., incision), the former floodplain it had been constructing may be abandoned. An abandoned floodplain is called a *terrace*. Terraces may be at different levels above the floodplain, depending on the past history of the individual river (Figure 41). When a river aggrades, the floodplain may reoccupy or become higher than adjacent terraces. The process of valley scour and redeposition is called "cut and fill". Analysis of alluvial history suggests that valley filling tends to be a much slower process than valley erosion (Leopold 1994). Many alluvial valleys consist of multiple floodplain and terrace surfaces.

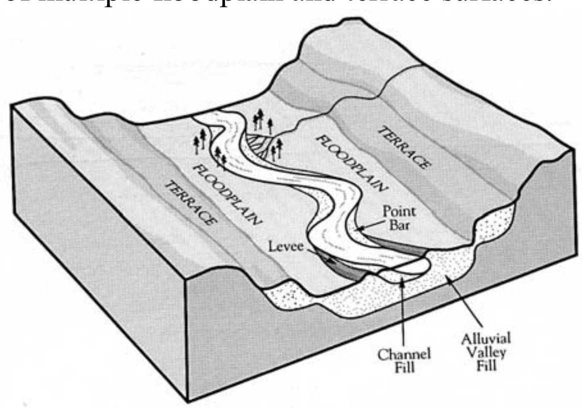


Figure 41. Cross- section and planview illustration of terrace development and valley downcutting and subsequent filling (Adapted from Mount 1995).

Terraces are susceptible to erosion by migrating channels, particularly when the terrace is composed of unconsolidated alluvium. Unlike the definition of floodplain, there is no consistency among rivers in the recurrence interval of flooding of the terraces that exist (e.g., very extreme flood events) (adapted from Dunne and Leopold 1978).

As with all natural systems, channels will develop the most stable configuration based on the existing conditions. However, rivers are inherently dynamic systems that constantly respond to variable inputs of water, wood, and sediment through erosion and deposition. For relatively constant conditions of the controlling variables, a natural river may develop characteristic forms, recognizable as statistical averages about which fluctuations occur. A change in discharge and sediment characteristics does not necessarily produce an immediate change in the stream channel but rather initiates a change that may extend over a period of time. Adjustment to changes in watershed conditions may take time and may not be completed before another event disrupts the condition, causing readjustment again. It is therefore not possible to forecast what will be the net effect of a particular or series of alterations. However, there are probable states (Leopold 1994).

River Pattern

River pattern is used to describe the planform geometry of a river reach or segment, as viewed from above as it would appear from an airplane, and implies the processes operating along that river. *Channel pattern* is used to define these characteristics only within individual channels that make up part of the overall river pattern (Nanson and Knighton 1996). Two main river patterns are generally recognized: single-channel rivers and anabranching rivers. *Anabranching* rivers are multi-channel systems characterized by vegetative or otherwise stable alluvial *floodplain islands* that divide flows at discharges up to nearly bankfull (Schumm 1985; Nanson and Knighton 1996). Channel pattern, as applied to individual channels, has been classically divided into straight, meandering and braided channels (Leopold and Wolman 1957). A simple diagram of these river and channel patterns is displayed in Figure 42, but more detailed analyses of different patterns also exist (Leopold and Wolman 1957; Brice 1978; Schumm 1985; Knighton and Nanson 1993; Nanson and Knighton 1996; Thorne 1998).

Due to hydrodynamics, nearly all natural channels exhibit some tendency to develop curves, or meanders in plan form, which seem to be proportional to the size of the channel. The *meandering* channel pattern is often illustrated as symmetrical bends, although the meanders can be asymmetrical or quite irregular. The exceptions to the meandering pattern occur where a stream is forced into a more or less *straight* channel pattern by land use intervention or through geologic controls like fractured bedrock or very cohesive sediment, and where high sediment loads produce a *braided* channel pattern. Even where the channel is straight it is usual for the *thalweg*, or line of maximum channel depth, to wander back and forth from near one bank to the other. Rivers are seldom straight through a distance greater than about ten channel widths, and so the designation straight is relative and implies an irregular, sinuous (non-meandering) alignment (Figure 42). Most rivers can also exhibit straight, meandering and braided patterns all within the same reach or valley segment depending on the scale of the observation.

A braided stream is divided into several channels that branch and rejoin around bare or sparsely vegetated sand/gravel/cobble bars. The braided form may range from occasional (widely separated single bars) to fully braided (many channels divided by many low bars). The braided channel pattern is partly stage or water level dependent. Bars exposed at most flows may be inundated at higher discharges to display the overall single-channel river pattern. Braided streams are characterized by high sediment load relative to transport capacity, wide active channels overall, low sinuosity, low threshold of bank erosion, rapid shifting of bed material, and a continuously shifting stream course (Knighton 1998). Rapidly fluctuating stream flow contributes to bed instability and bank erosion, common on streams fed by glaciers. Braiding involves the positive feedback cycle between sediment supply, bar formation, and bank erosion. Braided channels are also common in locations with a high sediment supply and a rapid reduction in transport capacity, such as alluvial fans when a steep mountain stream drops into a valley.

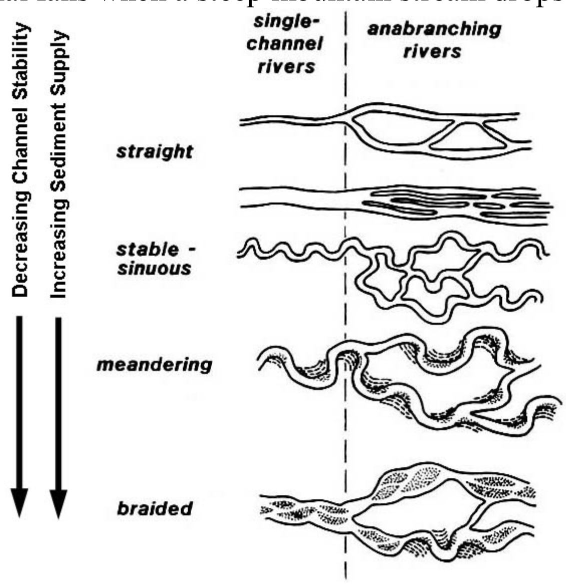


Figure 42. Single and Anabranching River Patterns (Modified from Nanson and Knighton 1996)

Anabranching rivers have multiple channels divided by semi-permanent floodplain islands, which are typically vegetated. Individual channels within anabranching rivers can be straight, meandering or braided (Figure 42). Anabranching streams typically retain the appearance of a multiple channel system up to the bankfull discharge, when floodwaters connect across forested island floodplains. As with braided streams, individual channels of an anabranching river are a response to relatively high sediment supply at varying scales. Multiple channels, each with relatively small width-depth ratios as compared to the overall channel, effectively increase the sediment transport capacity to accommodate the sediment load (Schumm 1985; Nanson and Knighton 1996). Numerous types of anabranching rivers have been described (see Channel Types below). Wood debris also plays a role in initiating and sustaining anabranching systems (Abbe and Montgomery 1996, 2003).

Anastomosing, a word borrowed from a medical term for dividing and rejoining blood vessels is used to describe a specific subset of anabranching rivers with erosion-resistant cohesive banks and relatively low width-depth ratios of individual channels. The lower width-depth ratios of anastomosing channels are partially supported by cohesive bank sediment, island vegetation root strength, and/or large woody debris bank protection (imbedded or instream) (Smith and Smith 1984; Knighton and Nanson 1993; Nanson and Knighton 1996). As with all anabranching rivers, vegetation plays a crucial role in creating anastomosing channels by providing bank cohesion and providing wood debris for channel creation (i.e., avulsion), maintenance, and stability (Nanson and Knighton 1996; Gurnell and Petts 2002; Abbe & Montgomery 2003).

Channel pattern represents a mode of channel form adjustment in the horizontal plane that is linked with other channel adjustments. The available evidence suggests that the sequence of straight, meandering and braided patterns is related to (Knighton 1984):

i) increasing width-depth ratio, which is generally associated with decreasing bank stability/resistance and increasing bed-load transport;
ii) increasing stream power, which implies increasing discharge at constant slope or increasing slope at constant discharge; and
iii) increasing sediment load and in particular bed load.

A particular channel shape and pattern is closely related to the quantity and variability of stream flow, the quantity and character of the sediment and wood in movement through the section, and the composition of the materials making up the bed and banks of the channel. Classifying channels based on pattern can tell us something about the current sediment and water regime, but a channel pattern can change from a large change in either of those inputs. For example, a channel may change from a single channel meandering pattern to a braided pattern and back to a meandering pattern in response to a large but temporary increase in sediment or short term reduction of bank resistance through vegetation loss. It is not uncommon for a non-braided channel to develop a side channel forced by the deposition of large wood at the upstream end of a gravel bar. A channel can also be highly sinuous and meandering but entirely confined by bedrock or very cohesive banks.

River pattern is a continuum from one extreme to another. There is no sharp distinction between any of these patterns, but empirical attempts have been made to separate them (Leopold et al. 1964). The current pattern of the channel is only one attribute looked at when attempting to predict future channel movement. Because plan form is a response to a complex array of interactive variables, it is not the sole discriminator for river classification or channel types. Although any classification of distinctive patterns or channel types is somewhat arbitrary, some sweeping statements can be made about the processes forming each general class. These generalities are expanded upon below.

Channel Types and Classification

Because a river channel can be characterized by a particular combination of patterns and attributes, channel classification is possible. Once classified, general statements can be made about the responsiveness of each channel type to changes in the controlling factors described above. Based on a combination of characteristics, we can broadly predict which stream channels will have a tendency to migrate over time and by what processes.

However, river channel morphologies do not always neatly fit into discrete compartmental types. Rivers should be viewed as a continuum (or discontinuum) of channel types, where one type blends gradually or abruptly into another depending on different processes and geomorphic thresholds (Kondolf et al 2003).

A number of classification schemes exist in the literature and are applied at different scales for different purposes. Defining the intended spatial scale of any classification scheme is important. Streams can be viewed as hierarchically organized, interlocked units nested within each other. The variability of the next lower level is constrained by the higher hierarchical level (Frissell et al. 1986; Kondolf et al. 2003). These hierarchical levels range from the river system or catchment scale, to the valley segment scale, to the reach scale, to the habitat scale, to the microhabitat scale (Figure 43) (Frissell et al. 1986). For the purposes of channel migration, the valley segment and reach scales are most appropriate. Fortunately, the majority of channel classification systems have focused at these scales.

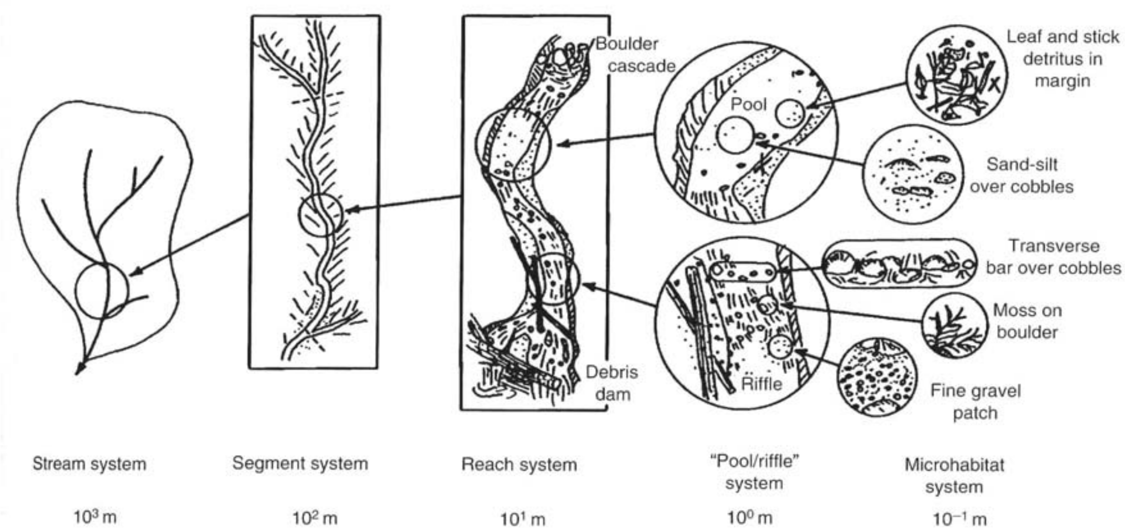


Figure 43. Hierarchical Stream Classification (Frissell et al. 1986; Adapted From Kondolf et al. 2003)

Several basic catchment-to-reach scale classifications of fluvial forms and processes have been reviewed above [i.e., 1) sediment erosion, transfer, and long-term storage zones (Schumm 1977); 2) bedrock, semi-controlled, and alluvial channels (Schumm 1985); 3) single-channel rivers and anabranching rivers (Nanson and Knighton 1996); 5) straight, meandering and braided channels (Leopold and Wolman 1957)]. While very useful, these classifications are only a few building blocks of more detailed reach and segment scale classifications.

All channel classifications use a combination of attributes to describe general channel types. Basic to many of these are 1) channel slope or gradient, 2) horizontal and vertical confinement of the channel (valley morphology), 3) relative channel size (function of drainage area and dominant discharge), 4) bank and bed material and size, 5) dominant mode of sediment transport, 6) channel pattern, 7) and available stream energy (stream power).

Several mountain drainage basin classifications exist for Washington State. Whiting and Bradley (1993) classify headwater channels based on process interactions between hillslopes and channels. Montgomery and Buffington (1993, 1997) use a process-based channel classification that relates morphological parameters to relative sediment supply and the ratio of sediment supply to transport capacity. While very useful for many streams in a mountain drainage network, these classifications are limited in their applicability to floodplain river systems and the assessment of migration potential through floodplain deposits.

Cupp (1989) developed a valley segment scale classification intended for basin-wide land management planning and research. Cupp's system focuses on six valley bottom and sideslope geomorphic characteristics thought to remain relatively persistent over a planning time scale. Grouped into four broad categories, any valley width to channel width ratio greater than 2 is generally considered "unconstrained" in this system. This type of classification can provide a relative measure of the valley size potentially available to channel migration.

Nanson and Croke (1992) give a genetic classification specific to floodplain morphology and functional processes in alluvial rivers. Their classification is based on a stream's competence and ability to do work. Primary classification variables include specific stream power and the erosional resistance of floodplain alluvium. *Specific stream power* is the potential energy per unit width of stream available to erode and transport sediment. It is a function of stream slope, discharge and channel width. The classification scheme is divided into three major distinct groups based mainly on stream power and sediment size. Sediment size of non-cohesive alluvium ranges from gravel to fine sand, while cohesive alluvium consists of silt and clay.

Class A: High-Energy Non-Cohesive Floodplains
Class B: Medium-Energy Non-Cohesive Floodplains
Class C: Low-Energy Cohesive Floodplains

Within this classification are a total of fifteen subgroups that differ according to specific stream power, sediment size, confinement, erosional and depositional or accretional processes, landforms, channel pattern, and catchment location.

Nanson and Knighton (1996) provide a classification of floodplain anabranching rivers, which are very common in Washington State. Again, their classification is primarily based on stream power (slope-discharge combinations) but also includes classification metrics on bed and bank material size, lateral migration rate, vertical accretion rate, channel sinuosity, and relative floodplain island size. They distinguish six different channel types, within which there are also several sub-types (Figure 44).

Channel type	Channel character	Unit stream power	Bed material	Bank material	Lateral migration rate	Vertical accretion rate	Channel sinuousity	Island length/channel width
1	Anastomosing	A	A	A	A	A	E	F
2	Sand-dominated, island forming	B	B	B	B	F	A	E
3	Mixed load, laterally active	C	C	C	C = /F =	C =	F	D
4	Sand-dominated, ridge forming	D	D	D	C = /D	B	B	C
5	Gravel-dominated, laterally active	E	E	E	F	C =	D	B
6	Gravel-dominated, stable	F	F	F	E/C =	E	C	A

A–F: relative strength of variable, either LOW (A) to HIGH (F) or FINE (A) to COARSE (F).

Figure 44. Summary of variables linked to channel adjustment, morphology and classification in floodplain alluvial rivers (Nanson and Knighton 1996; after Gurnell and Petts 2002).

These two process-based, floodplain classification systems (i.e., Nanson and Crooke 1992; Nanson and Knighton 1996) can be utilized separately or in combination, due to their overlapping attributes. Once classified by these variables, a channel can be assessed for the dominant processes operating to build and erode floodplain deposits and its relative potential to migrate and rework these deposits.

Channel classification is useful for identifying or screening for channels prone to migration and, if assessed correctly, will provide clues to the generalized processes operating within a stream reach or segment. It also provides a technical basis for communication regarding river systems. However, the existing classification systems were not designed to predict delineation lines of channel migration zones on the ground. The dynamic behavior of channels through space and time at a unique location along the river discontinuum cannot be fully captured by channel classification, as it is not an absolute predictive tool.

Summary

The technical information provided in this background serves as a common language to describe and analyze streams prone to channel migration. While detailed scientific quantification of channel form and process is always possible, in most cases it is not necessary to proceed to this level of detail to generally understand a stream system or delineate a channel migration zone. However, at least a qualitative understanding of forms and processes at work in a given stream reach or segment is essential to guide a CMZ delineator in their attempt to predict future channel locations. This essential understanding of a river system, as defined above, includes: 1) the watershed's landscape location (e.g., climate, geology, land use); 2) segment location in the river discontinuum (e.g., upland valley vs. lowland valley); 3) valley segment four-dimensional configuration (e.g., confined vs. unconfined); 4) general magnitude and frequency of water, sediment and wood inputs and their disturbance effects; 5) floodplain building processes (e.g., combination of avulsion and bank erosion); 6) river pattern and plan form (e.g., inferences of fluvial processes at work); 7) cycles of channel adjustment and evolution through time (e.g., relative changes in bed elevation or channel pattern); and 8) an appreciation of the complex interaction of all these forms and processes over time.

Stream classification systems attempt to incorporate some or all of these variables to describe the responsiveness of a given stream to changes in the controlling factors and predict a stream's tendency to migrate over time. Once a stream is classified and at least qualitatively understood, communication regarding management options will be greatly enhanced.

2.6 Glossary

As used in this manual, the following terms are defined as:

abandoned channel: Any *channel* feature that was once more active in water and sediment transport than in its current form. Often partially filled in or blocked at the upstream end with sediment, duff, or debris. No reference to time or location. Could be formed from active and recent processes or processes and conditions no longer operating and masked by sediment and organic material infilling. Can either be on a terrace or floodplain.
active channel: That portion of the channel or floodplain network that receives periodic scour and/or fill during sediment transport events.
aggradation: An increase in sediment supply and/or decrease in sediment transport capacity that leads to an increase in the channel bed elevation. An increase in base level can also decrease sediment transport capacity, thereby initiating aggradation.
alluvial fan: A cone or fan-shaped deposit of sediment and debris that accumulate immediately below a significant change in channel gradient and/or valley confinement Viewed from above, it has the shape of an open fan, the apex being at the valley mouth where the stream.
alluvium / alluvial: A general term for or pertaining to deposits made by streams on river beds, flood plains, and alluvial fans.
anabranch: A diverging branch or *secondary channel* of a river, which reenters the mainstream some distance downstream.
anabranching: A river pattern with multi-channels characterized by vegetative or otherwise stable alluvial *floodplain islands* that divide flows at discharges up to nearly bankfull. Individual channels may be straight, meandering or braided.
anastomosing channel: A river pattern (subset of anabranching) with multiple, interconnected, coexisting channels separated by *floodplain islands*, with erosion-resistant cohesive banks, and relatively low width-depth ratios of individual channels.
avulsion: Relatively sudden and major shifts in the position of the channel to a new part of the floodplain (first-order avulsion) or sudden reoccupation of an old channel on the floodplain (second-order avulsion) or relatively minor switching of channels within a braid train or other active channels (third-order avulsion) (Nanson and Knighton 1996).
Avulsion Hazard Zone (AHZ): The area not included in the HMZ where the channel is prone to move by avulsion and if not protected would result in a potential near-term loss of riparian function and associated habitat adjacent to the stream.
bankfull stage: The height at which the channel overflows its banks, corresponding approximately to the discharge at which the channel characteristics are maintained.
braided : a channel pattern that is divided into several channels that branch and rejoin around bare or sparsely vegetated sand/gravel/cobble bars.
channel (watercourse)**:** Any open conduit or linear depressional feature either naturally or artificially created or cut by fluvial processes (i.e., erosion plus deposition), which periodically or continuously (i.e., intermittent or perennial) contains moving water, or which forms a connecting link between two bodies of water.

channel evolution: Lateral and vertical adjustments in channel form over time, along with changes in *channel pattern.*
channel pattern: The planform geometry of a river channel, as viewed from above as it would appear from an airplane. Only used to describe individual channels that make up part of the overall *river pattern*.
chutes: Small *secondary channels* used during flow or flood pulses only. Typically chutes flow across the convex side of meander bends through floodplain deposits, between sequential riffles above and below meander bends, and along steeper flow paths than the main river channel.
chute cutoff: A reach scale *avulsion* that erodes a channel behind a point bar deposit either through a *chute* (second-order *avulsion*) or the general floodplain (first-order *avulsion*).
confinement or valley confinement: A measure of the degree to which a channel is bounded by hillslopes or other resistant landform, usually expressed as a ratio of the average channel width to valley bottom width.
debris flow: A moving mass of rock fragments, soil, and mud, more than half of the particles being larger than sand size.
degradation: An decrease in sediment supply and/or increase in sediment transport capacity that leads to an decrease in the channel bed elevation through incision or downcutting. A decrease in base level can also increase sediment transport capacity, thereby initiating degradation or incision.
dike or levee (constructed): A continuous structure from valley wall to valley wall or other geomorphic feature that acts as an historic or ultimate limit to lateral channel movements and is constructed to a continuous elevation exceeding the 100-year flood stage (1% exceedence flow); or a structure that supports a public right-of-way or conveyance route and receives regular maintenance sufficient to maintain structural integrity.
Disconnected Migration Area (DMA): The portion of the CMZ behind a permanently maintained dike or levee.
distributary channel: A *secondary channel* that branches from the main channel but does not rejoin. These typically occur at the mouth or delta of a river where it empties in a lake or ocean or on an alluvial fan.
Entrenchment: The vertical containment of a river and the degree to which it is incised within a valley floor, as seen by the relationship between the channel and the relatively flat surfaces on the valley floor that may be prone to flooding at some maximum stream discharge
Erosion Hazard Area (EHA): Those areas outside of the HMZ and AHZ which are susceptible to bank erosion and retreat from stream flow and this can result in a potential near-term loss of riparian function and associated habitat adjacent to the stream
flood frequency: Refers to a flood level that has a specified percent chance of being equaled or exceeded in any given year. For example, a 100-year flood occurs on average once every 100 years and thus has a 1-percent chance of occurring in a given year. (Recurrence Interval: the average time interval in years in which a flow of a given magnitude will recur)
floodplain: The relatively flat area or berm adjoining a river channel and constructed by the river in the present climate by a combination of progressive lateral migration, channel

creation and abandonment, and overbank sediment deposition from periodic inundation. Floodplains may not be uniform or homogeneous flat surfaces, and can consist of irregular or multiple surfaces at different elevations that reflect vertical differences in the channel bed resulting from local scour, changes in flow regime, sediment supply and wood loading. See complete definition in Section 2.2 Determining if Channel Migration Is Present

floodplain island: A body of land located within the active river channel completely surrounded by water during moderate flow or flood pulses, which can be completely inundated during larger floods.

flood-prone width: the width of the stream at some maximum stream discharge.

gradient: The slope of the stream channel, valley, floodplain, or terrace in the downstream direction usually expressed as a ratio of vertical rise to horizontal run. Channel gradient can either be measured as the thalweg slope or water surface slope.

Historic Migration Zone (HMZ): The sum of all active channels over the historical period that usually includes the time between the year 1900 and the present – the approximate time period sufficient to capture pre-timber harvest channel conditions. This time period is extended for those sites known to have been impacted by timber harvest activities prior to 1900, or where historical information such as Government Land Office maps and notes are available.

lahar: A mixture of water and rock debris (mudflow) composed chiefly of pyroclastic material on the flanks of a volcano.

lateral erosion: The wearing down or washing away of the stream bank, soil and land surface by the action of water as the stream swings from side to side, impinging against and undercutting its banks.

levee (natural): A longitudinal (flood) berm of sediment along the channel bank. Results from sediment (silt to boulder) deposition dropped from suspension or movement during floods. Occurs where water passes from a deep channel to shallow flow and where turbulence abruptly drops along channel margins.

main channel: The main stream channel is the dominant channel with the deepest or lowest thalweg, the widest width within defined banks, and the most water during low flow periods. Main channel locations can be transient over time. Braided channels may not have a defined main channel, especially as stages reach bankfull.

meandering: a channel pattern of stream curves in plan form (symmetrical bends, asymmetrical or irregular), which seem to be proportional to the size of the channel. Meandering is a pattern and does not necessarily imply bank erosional processes at work in the channel.

meander belt: The area between the limits of the amplitude of the meander bends. Typically, parallel lines are drawn to encompass the maximum amplitude of the meander wave and any meander cutoffs or oxbow lakes in a given stretch of river. Multiple sets of parallel lines are usually drawn to encompassed meander belts along sinuous valleys.

meander scrolls: Individual *ridge-swale* pairs oriented in a curvilinear fashion along the convex side of meander bends.

neck cutoff: A reach scale *avulsion* that erodes a channel through a floodplain deposit (first- or second-order *avulsion)* connecting two previously separated meander bends.

overflow channel: A *secondary channel* on the floodplain that conveys water away from and/or back into the main channel. These channels can be continuous or interrupted in

space in terms of channel dimensions and scour and fill. They often are a response to episodic flood scour and fill during floodplain inundation and drainage. They also can partially fill in between episodic flood events or become *abandoned* completely or be blocked by deposits of sediment or wood at their head. Overflow channels are typically at or above the range of bankfull flow elevations.
oxbow lake: A crescent shaped pond or lake formed in a portion of abandoned stream channel cut off from the rest of the main channel created when meanders are cut off by *avulsions* from the rest of the channel. Once isolated by formation of avulsion channels, oxbow lakes will slowly fill up with sediment, as point bar sands and gravels are buried by silts, clays, and organic material carried in by river floods and by sediment slumping in from sides as rain fills up lake.
point bar: Accumulations of fluvial sediment at the relatively gentle slope of the inside of a *channel* bend or curve.
river pattern: the planform geometry of a river reach or segment, as viewed from above as it would appear from an airplane, and implies the processes operating along that river. The river pattern includes the individual channels patterns with in the reach or segment.
secondary channel: Any *channel* on or in a floodplain that carries water (intermittently or perennially in time; continuously or interrupted in space) away from, away from and back into, or along the main channel. Secondary channels include: *side channels, wall-based channels, distributary channels, anabranch channels, abandoned channels, overflow channels, chutes, and swales*.
segment or channel segment: Lengths of stream that have similar valley confinement, discharge, channel pattern, and average valley gradient.
side channel: A *secondary or anabranch channel* that is at least partially connected to the main river channel with its channel thalweg at or below the range of bankfull flow elevations. Side channel inlets are often blocked by wood jams or large accumulations of gravel and sand.
sinuosity: A measure of the extent of river meandering usually applied to single channels and expressed as the ratio of channel thalweg length to straight-line valley length.
slough: An area of slack (not moving) water formed in a *meander scroll* deposit (*swale*) or an *abandoned channel* still partially connected to the main river at its downstream end. During flood stage, sloughs can become reconnected at their upstream end.
straight: a channel pattern in plan form where a stream is forced into a more or less non-curved channel pattern by land use intervention or through geologic controls like fractured bedrock or very cohesive sediment.
specific stream power: the potential energy per unit width of stream available to erode and transport sediment.
surface or floodplain surface: A constant feature up and down the valley that lies at a relatively consistent elevation above bankfull and was formed by a discrete process at a discrete point in time, resulting in consistent soil development and other age indicators. See section 2.3 under Channel Migration Zone Components.
swales: Small *secondary channel* or linear depressional features on point bar deposits. Associated with the point bar are a series of arcuate *ridges* and *swales*. The *ridges* are formed by lateral channel movement and are relic lateral bars separated by low-lying

swales. S*wales* are locations where fine-grained sediments accumulate following original creation. See Figure 37 in background section.
terrace: A former or relict floodplain no longer inundated by flood water given the current climate. See complete definition in Section 2.2 Determining if Channel Migration Is Present
thalweg: The longitudinal line that defines the deepest part of the channel or stream bed.
underfit stream: A river or stream that appears too small to have eroded the valley in which it occupies.
wall-based channel: A *secondary channel* formed on floodplains or terraces that follows linear depressional features created by channel migration or floodplain deposition of the mainstem river near the base of valley walls or terraces. They typically flow parallel to a mainstem river along the floodplain before joining the river. These channels can be *anabranch or secondary channels* of the main river, or tributary channels. Water sources can originate from a combination of hillslope tributary input, hillslope seepage, groundwater input (i.e., springs or diffuse), river water input, and direct local precipitation.

2.7 References

Abbe, T.B. 2000. Patterns, mechanics and geomorphic effects of wood debris accumulations in a forest river system. University of Washington, PhD Dissertation, Seattle, WA.

Abbe, T.B., Brooks, A.P., and Montgomery, D.R. 2003. Wood in River Rehabilitation and Management . *In* The Ecology and Management of Wood in World Rivers. *Edited by* S.V. Gregory, K.L. Boyer, and A.M. Gurnell. American Fisheries Society , Bethesda, MD.

Abbe, T.B. and Montgomery, D.R. 1996. Large Woody Debris Jams, Channel Hydraulics and Habitat Formation in Large Rivers. Regulated Rivers: Research and Management **12**: 201-221.

Abbe, T.B. and Montgomery, D.R. 2003. Patterns and Processes of Wood Debris Accumulation in the Queets River Basin, Washington. Geomorphology **51**: 81-107.

Booth, D.B. 1990. Stream-Channel Incision Following Drainage-Basin Urbanization. Water Resources Bulletin **26**: 407-417.

Booth, D.B., Haugerud, R.A., and Troost, K.G. 2003 The Geology of Puget Lowland Rivers. *In* Restoration of Puget Sound Rivers. *Edited by* D.R. Montgomery, S.M. Bolton, D. Booth, and L. Wall. University of Washington Press, Seattle, WA pp. 14-45.

Booth, D.B. and Jackson, C.R. 1997. Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation. Journal of the American Water Resources Association **33**: 1077-1089.

Bosch, J.M. and Hewlett, J.D. 1982. A Review of Catchment Experiments to Determine the Effect of Vegetation Changes on Water Yield and Evapotranspiration. Journal of Hydrology **55**: 3-23.

Brice, J.C., Blodgett, J.C., and et al. 1978. Countermeasures for Hydraulic Problems at Bridges, Volume 1 and 2. Federal Highway Administration Report FHWA-RD-78-163, Washington D.C.

Bridge, J.S. 2003. Rivers and Floodplains: Forms, Processes, and Sedimentary Record. Blackwell, Oxford, UK.

Brooks, A.P. , Brierley, G.J., and Millar, R.G. 2003. The Long-term Control of Vegetation and Woody Debris on Channel and Flood-plain Evolution: Insights from a Paired Catchment Study in Southeastern Australia. Geomorphology **51**: 7-29.

Chang, H.H. 1988. Fluvial Processes in River Engineering. John Wiley and Sons, New York.

Church, M. 2002. Geomorphic Thresholds in Riverine Landscapes. Freshwater Biology **47**: 541-557.

Collins, B.D., Montgomery, D.R., and Sheikh, A.J. 2003. Reconstructing the Historical Riverine Landscape of the Puget Lowland. *In* Restoration of Puget Sound Rivers. *Edited by* D.R. Montgomery, S.M. Bolton, D. Booth, and L. Wall. University of Washington Press, Seattle, WA pp. 79-128.

Cupp, C.E. 1989. Stream Corridor Classification for Forested Lands of Washington. State of Washington, Timber/Fish/Wildlife, Ambient Monitoring Program, Olympia, WA.

Dunne, T. and Leopold, L.B. 1978. Water in Environmental Planning. W.H. Freeman, San Francisco.

Frissell, C.A., Liss, W.J., Warren, C.E., and Hurley, M.D. 1986. A Hierarchical Framework for Stream Habitat Classification: Viewing Stream in a Watershed Context. Environmental

Management **10**: 199-214.

Galay, V.J., Kellerhals, R., and Bray, D.I. 1973. Diversity of River Types in Canada. *In* Fluvial Processes and Sedimentation. *Edited by* Proceedings of Hydrology Symposium. National Research Council of Canada, pp. 217-250.

Gippel, C.J. , O'Neill, I.C., Finlayson, B.L., and Schnatz, I. 1996. Hydraulic Guidelines for the ReIntroduction and Management of Large Woody Debris in Lowland River Systems. Regulated Rivers Research and Management **12**: 223-236.

Gurnell, A.M. and Petts, G.E. 2002. Island-Dominated Landscapes of Large Floodplain Rivers: a European Perspective. Freshwater Biology **47**: 581-600.

Gustard, A. 1994. Analysis of River Regimes. *In* The Rivers Handbook: Hydrological and Ecological Principles; Volume One and Two . *Edited by* P. Calow and G.E. Petts. Blackwell Scientific Publications, Oxford, United Kingdom pp. 29-47.

Hogan, D.L., Bird, S.A., and Rice, S.P. 1998. Stream Channel Morphology and Recovery Processes. *In* Carnation Creek and Queen Charlotte Islands Fish/Forestry: Applying 20 Years of Coastal Research and Management Solutions. *Edited by* D.L. Hogan, P.J. Tschaplinski, and S. Chatwin. B.C. Ministry of Forests, Land Management Handbook No. 41, Victoria B.C. pp. 77-96.

Hollis, G.E. 1975. The Effects of Urbanization on Floods of Different Recurrence Interval. Water Resources Research **11**: 431-435.

Jones, J.A. and Grant, G.E. 1996. Peak Flow Responses to Clear-Cutting and Roads in Small and Large Basins, Western Cascades, Oregon. Water Resources Research **32**: 959-974.

Jones, J.A. and Post, D.A. 2004. Seasonal and Successional Streamflow Response to Forest Cutting and Regrowth in the Northwest and Eastern United States. Water Resources Research **40**: WO5203.

Jones, L.S. and Schumm, S.A. 1999. Causes of Avulsion: An Overview. *In* Fluvial Sedimentology VI *Edited by* N.D. Smith and J. Rogers. International Association of Sedimentologists, Special Publication 28, Blackwell Science, Oxford, U.K. pp. 171-178.

Kellerhals, R. and Church, M. The Morphology of Large Rivers: Characterization and Management. Dodge, D. P. The International Large River Symposium. 89.

Kellerhals, R., Neill, C.R., and Bray, D.I. 1972. Hydraulic and Geomorphic Characteristics of Rivers in Alberta. Research Council of Alberta, River Engineering and Surface Hydrology Report 72-1.

Knighton, A.D. and Nanson, G.C. 1993. Anastomosis and the Continuum of Channel Pattern Earth Surface Processes and Landforms **18**: 613-625.

Knighton, D. 1999. Downstream Variation in Stream Power. Geomorphology **29**: 293-306.

Knighton, D. 1984. Fluvial Forms and Processes Arnold, London.

Knighton, D. 1998. Fluvial Forms and Processes: A New Perspective. Arnold, London.

Kondolf, G.M., Montgomery, D.R., Piegay, H., and Schmitt, L. 2003. Geomorphic Classifications of Rivers and Streams. *In* Tools in Fluvial Geomorphology. *Edited by* G.M. Kondolf and H. Piegay. John Wiley and Sons., West Sussex, U.K. pp. 171-204.

Lancaster, S.T., Hayes, S.K., and Grant, G.E. 2001. Modeling Sediment and Wood Storage and Dynamics in Small Mountainous Watersheds. *In* Geomorphic Processes and Riverine Habitat. *Edited by* J.M. Dorava, D.R. Montgomery, B.B. Palcsak, and F.A. Fitzpatrick. American

Geophysical Union, Water Science and Application 4, Washington D.C. pp. 85-102.

Leopold, L.B. 1994. A View of a River. Harvard University Press.

Leopold, L.B. and Wolman, M.G. 1957. River Channel Patterns: Braided, Meandering and Straight. United States Geological Survey Professional Paper 282B.

Leopold, L.B., Wolman, M.G., and Miller, J.P. 1964. Fluvial Processes in Geomorphology. Dover, New York.

Lewis, G.W. and Lewin, J. 1983. Alluvial Cut-offs in Wales and the Borderlands. *In* Modern and Ancient Fluvial Systems. *Edited by* J.D. Collinson and J. Lewin. Blackwell, Special Publication of the International Association of Sedimentologists, Oxford, United Kingdom pp. 145-154.

Lewis, J., Mori, S.R., Keppeler, E.T., and Ziemer, R.R. 2001. Impacts of Logging on Storm Peak Flows, Flow Volumes and Suspended Sediment Loads in Casper Creek, California. *In* Land Use and Watersheds: Human Influences on Hydrology and Geomorphology in Urban and Forest Areas. *Edited by* M.S. Wigmosta and S.J. Burges. American Geophysical Union, Water Science and Application 2, Washington D.C. pp. 85-125.

Lisle, T.E. 1982. Effects of Aggradation and Degradation on Riffle-Pool Morphology in Natural Gravel Channels, Northwestern California . Water Resources Research **18**: 1643-1651.

Lisle, T.E. 1995. Effects of Coarse Woody Debris and Its Removal on a Channel Affected by the 1980 Eruption of Mount St. Helens, Washington. Water Resources Research **31**: 1797-1808.

Lisle, T.E. and Napolitano, M.B. 1998. Effects of Recent Logging on the Main Channel of North Fork Caspar Creek. *In* Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story. *Edited by* R.R. Ziemer. U.S.D.A., Pacific Southwest Research Station, Forest Service.

Mackin, J.H. 1948. Concept of the Graded River . University of Washington, Seattle, WA.

Maser, C. and Sedell, J.R. 1994. From the Forest to the Sea: The Ecology of Wood in Streams, Rivers, Estuaries and Oceans. St. Lucie Press , Delray Beach, FL.

Massong, T.M. and Montgomery, D.R. 2000. Influence of Sediment Supply, Lithology, and Wood Debris on the Distribution of Bedrock and Alluvial Channels. Bulletin of the Geological Society of America **112**.

Montgomery, D.R. 1999. Process Domains and the River Continuum. Journal of the American Water Resources Association **35**: 397-410.

Montgomery, D.R., Abbe, T.B., Buffington, J.M., Peterson, N.P., Schmidt, K.M., and Stock, J.D. 1996. Distribution of Bedrock and Alluvial Channels in Forested Mountain Drainage Basins. Nature **381**: 587-589.

Montgomery, D.R. and Buffington, J.M. 1993. Channel classification, prediction of channel response, and assessment of channel condition. Timber/Fish/Wildlife Report TFW-SH10-93-002, Seattle, WA.

Montgomery, D.R. and Buffington, J.M. 1997. Channel-Reach Morphology in Mountain Drainage Basins. Geological Society of America Bulletin **109**: 596-611.

Mount, J.F. 1995. California Rivers and Streams. University of California Press, Berkeley, CA.

Nanson, G.C. and Croke, J.C. 1992. A Genetic Classification of Floodplains. Geomorphology **4**: 459-486.

Nanson, G.C. and Knighton, A.D. 1996. Anabranching Rivers: Their Cause, Character and Classification. Earth Surface Processes and Landforms **21**: 217-239.

National Research Council 1996. Alluvial Fan Flooding. National Academy Press, Washington D.C.

O'Connor, J.E., Jones, M.A., and Haluska, T.L. 2003. Flood Plain and Channel Dynamics of the Quinault and Queets Rivers, Washington, USA. Geomorphology **51**: 31-59.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C. 1997. The Natural Flow Regime: A Paradigm for River Conservation and Restoration . BioScience **47**: 769-784.

Poole, G.C. 2002. Fluvial Landscape Ecology: Addressing Uniqueness within the River Discontinuum. Freshwater Biology **47**: 641-660.

Rapp, C.F., and Abbe, T.B. 2003. A Framework for Delineating Channel Migration Zones. Washington State Department of Ecology and Washington State Dept. of Transportation; Ecology Final Draft Publication #03-06-027.

Rice, S. and Church, M. 1998. Grain Size Along Two Gravel-bed Rivers: Statistical Variation, Spatial Pattern and Sedimentary links. Earth Surface Processes and Landforms **23**: 345-363.

Rosgen, D.L. 1994. A Classification of Natural Rivers . Catena **22**: 169-199.

Schumm, S.A. 1977. The Fluvial System. Wiley-Interscience, New York.

Schumm, S.A. 1985. Patterns of alluvial rivers Annual Review of Earth and Planetary Science **13**: 5-27.

Sedell, J.R. and Luchessa, K.J. 1982. Using the Historical Record as an Aid to Salmonid Habitat Enhancement. *In* Acquisition and Utilization of Aquatic Habitat Inventory Information: Symposium Proceedings. *Edited by* N.B. Armantrout. The Hague Publishing, Billings, MT pp. 210-223.

Shields, F.D.Jr. and Gippel, C.J. 1995. Prediction of Effects of Woody Debris Removal on Flow Resistance . Journal of Hydraulic Engineering **121**.

Sidle, R.C., Pearce, A.J., and O'Loughlin, C.L. 1985. Hillslope stability and land use. American Geophysicists Union Water Resources Monograph #11.

Simon, A. 1994. Gradation processes and channel evolution in modified west Tennessee streams process, response, and form. USGS , Denver, CO.

Simon, A. and Hupp, C.R. 1986. Channel Widening Characteristics and Bank Slope Development along a Reach of Cane Creek, West Tennessee. USGS Water-Supply Paper 2290. Denver, CO.

Simon, A. and Hupp, C.R. 1992. Geomorphic and Vegetative Recovery Processes Along Modified Stream Channels of West Tennessee. USGS; Open-File Report 91-502, Denver, CO .

Simon, A. and Hupp, C.R. 1987. Geomorphic and Vegetative Recovery Processes along Modified Tennessee Streams: An Interdisciplinary Approach to Disturbed Fluvial Systems. *In* Forest Hydrology and Watershed Management. *Edited by* International Association of Hydrological Sciences. International Association of Hydrological Sciences, Washington, DC.

Smith, D.G. and Smith, N.D. 1980. Sedimentation in Anastomosed River Systems: Examples from Alluvial Valleys Near Banff, Alberta. Journal of Sedimentary Petrology **50**: 157-164.

Stednick, J.D. 1996. Monitoring the Effects of Timber Harvest on Annual Water Yield. Journal of

Hydrology **176**: 79-95.

Sullivan, K., Lisle, T.E., Dolloff, C.A., Grant, G.E., and L.M. Reid, L.M. 1987. Stream channels: The link between forests and fishes. *In* Streamside Management: Forestry and Fisheries Interactions. *Edited by* E.O. Salo and T.W. Cundy. Institute of Forest Resources Contribution, No. 57, University of Washington , Seattle, Washington pp. 39-97.

Thomas, R.B. and Megahan, W.F. 1998. Peak Flow Responses to Clear-Cutting and Roads in Small and Large Basins, Western Cascades, Oregon: A Second Opinion. Water Resources Research **34**: 3393-3403.

Thompson, D.M. 2003. A Geomorphic Explanation for a Meander Cutoff Following Channel Relocation of a Coarse-Bedded River. Environmental Management **31**: 385-400.

Thorne, C.R. 1998. Stream Reconnaissance Handbook: Geomorphogical Investigation and Analysis of River Channels. John Wiley and Sons, Chichester, UK.

Tockner, K., Malard, F., and Ward, J.V. 2000. An Extension of the Flood Pulse Concept. Hydrological Processes **14**: 2861-2883.

Triska, F.J. 1984. Role of Wood Debris in Modifying Channel Geomorphology and Riparian Areas of a Large Lowland River Under Pristine Conditions: A Historical Case Study. Verhandlung Internationale Vereinigung Limnologie **22**: 1876-1892.

Vannote, R.L., Minsall, G.W., Cummins, K.W., Sedell, J.R., and Cushing, C.E. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Science **37**: 103-137.

Ward, J.V. and Stanford, J.A. 1995. The Serial Discontinuity Concept: Extending the Model to Floodplain Rivers. Regulated Rivers: Research and Management **10**: 159-168.

Ward, J.V. and Stanford, J.A. 1983. The Serial Discontinuity Concept of Lotic Ecosystems. *In* Dynamics of Lotic Ecosystems. *Edited by* T.D Fontaine and S.M. Bartell. Ann Arbor Science, Ann Arbor.

Ward, J.V., Tockner, K., Arscott, D.B., and Claret, C. 2002. Riverine Landscape Diversity. Freshwater Biology **47**: 517-539.

Whiting, P.J. and Bradley, J.B. 1993. A Process-Based Classification System for Headwater Streams. Earth Surface Processes and Landforms **18**: 603-612.

Wohl, E.E. 2000. Mountain Rivers. American Geophysical Union, Water Resources Monograph 14, Washington D.C.

Wolff, H.H. 1916. The Design of a Drift Barrier Across the White River, Near Auburn, Washington. Transactions of the American Society of Civil Engineers **16**: 2061-2085.

Wolman, M.G. and Leopold, L.B. 1957. River Flood Plains: Some Observations on thier Formation U.S. Geological Survey, Professional Paper 282-C, Washington D.C.

Wolman, M.G. and Miller, J.P. 1960. Magnitude and Frequency of Forces in Geomorphic Processes. Journal of Geology **68**: 54-74.

WSDNR, USFWS, USNMFS, USEPA, WDFW, WSDOE, Washington State Tribes, Washington State Association of Counties, Washington Forest Protection Association, and Washington Farm Forestry Association. 1999. Forests and Fish Report. Olympia, WA.